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EVALUATION OF MATCHED FILTERS AND THE THREE-COMPONENT ADAPTIVE PROCESSOR FOR THE VLPE STATIONS AND VLPE NETWORK. TECHNICAL REPORT NO. 5. VELA NETWORK EVALUATION AND AUTOMATIC PROCESSING RESEARCH

Alan C. Strauss, et al

Texas Instruments, Incorporated

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# EVALUATION OF MATCHED FILTERS AND THE THREE-COMPONENT ADAPTIVE PROCESSOR FOR THE VLPE STATIONS AND VLPE NETWORK

## TECHNICAL REPORT NO. 5

## VELA NETWORK EVALUATION AND AUTOMATIC PROCESSING RESEARCH

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This report describes the evaluation of the chirp matched filter, the reference waveform matched filter, and the three-component adaptive processor in terms of events from two seismic regions and one presumed explosion test region as recorded by stations of the Very Long Period Experiment.

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19. Cont. Reference Waveform Matched Filter
Three-component Adaptive Processor

20. Cont. The major fields of study in this evaluation were:

- dB Signal-to-noise ratio improvement
- Detection level improvements
- Surface-wave magnitude computations for events not detected on the bandpass filter.

The three data enhancement techniques are compared with each other in terms of these fields of study with the intent of determining the best of the techniques.

# ABSTRACT

This report describes the evaluation of the chirp filter, the reference waveform matched filter, and the three-component adaptive processor in terms of events from two seismic regions as recorded by stations of the Very Long Period Experiment.

The major fields of study in the evaluation were:

- dB signal-to-noise ratio improvement
- detection level improvements
- surface-wave magnitude computations for events not detected on the bandpass filter.

The three data enhancement techniques are compared with respect to these areas to determine the best technique.

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# SECTION I
# INTRODUCTION

## A. GOALS

Surface waves often arrive at stations located at teleseismic distances from the epicenter with amplitudes at or below the noise level. In order to detect such signals and determine their magnitudes, special processing techniques must be employed. Three such techniques are evaluated in this report using data from the Very Long Period Experiment. They are: chirp matched filters (CMF), reference waveform matched filters (RWMF), and the three-component adaptive processor (TCA).

The specific goals of this study are:

- To estimate potential signal-to-noise ratio gains of each of these techniques.
- To evaluate the effectiveness of these three techniques in increasing the surface-wave detection capability of the VLPE stations.
- To apply the signal-to-noise ratio improvement estimates to the calculation of surface-wave magnitudes for events which were not detected on the bandpass-filtered traces.
- To compare the relative effectiveness of the three techniques.

## B. RESULTS FROM PREVIOUS STUDIES

A preliminary evaluation of these techniques as applied to VLPE data was presented in Special Report No. 14 (Lambert et al., 1973),

where the application of each technique to events having epicenters in a small region of Sinkiang Province, China was discussed. Conclusions were limited by the small amount of observational data available. The preliminary evaluation did indicate that appropriate chirp matched filters performed essentially the same as reference waveform matched filters when matched with Rayleigh waves. The use of matched filters decreased the number of non-detected events by 36 percent. Both chirp and reference waveform matched filters yielded signal-to-noise ratio improvements of 3.5 dB for earthquakes and 3.7-3.8 dB for presumed explosions. The three-component adaptive processor yielded detection results comparable to those for the chirp matched filter.

Analysis of data recorded at the Alaskan Long Period Array (ALPA) (Strauss, 1973) indicated that chirp matched filters were slightly more effective than reference waveform matched filters, that matched filters reduced the number of non-detected events by 20 percent, and that the greatest change in the detection versus bodywave magnitude plots caused by inclusion of these detections occurred at the 50 percent detection level.

Analysis of data recorded at the Norwegian Seismic Array (NORSAR) (Laun et al., 1973) indicated that reference waveform matched filters were slightly more effective than chirp matched filters, that matched filters reduced the number of non-detected events by about 10 percent, and that inclusion of these detections in the detection versus bodywave magnitude plots decreased the detection levels between the 30 percent and 80 percent detection levels. (The three-component adaptive processor was not applied to ALPA or NORSAR data.)

## C. SIGNAL-PLUS-NOISE-TO-NOISE RATIO IMPROVEMENTS

One of the methods of comparing the performance of the three data enhancement techniques under consideration was in terms of signal-to-noise ratio improvement over the equivalent bandpass filter (0.023-0.059 Hz) signal-to-noise ratio. The signal-to-noise ratio improvement of a matched filtered trace over the corresponding bandpass filtered trace, expressed in decibels, is:

$$\text{IMPROVEMENT (dB)} = 20 \log_{10} \left[ (S_M/N_M)/(S_{BP}/N_{BP}) \right]$$

Or, in a more convenient computational form:

$$\text{IMPROVEMENT (dB)} = 20 \log_{10} \frac{S_M}{S_{BP}} + 20 \log_{10} \frac{N_{BP}}{N_M}$$

where S and N are the peak signal and the RMS noise amplitude, respectively, the M subscript denotes matched filter, and the BP subscript denotes band-pass filter.

Since the manner in which the VLPE data was edited often precluded the existence of a noise sample of suitable length on the edited signal trace, the values of $N_{BP}$ and $N_M$ in the above equation were determined from a noise sample of the same day.

Since the signals are not noise free, the signal amplitudes are actually signal-plus-noise amplitudes. Therefore, we will refer to the signal-plus-noise-to-noise ratio (SNNR) from this point on.

In Section II of this report, the data base is presented in detail, with a complete listing of event parameters, description of available stations, and discussion of the data quality. Section III presents the

analysis of the chirp matched filter data, Section IV the analysis of the reference waveform matched filter data, and Section V of the analysis of the three-component adaptive processor data. Section VI presents the comparison of the three techniques and conclusions based on these comparisons.

SECTION II

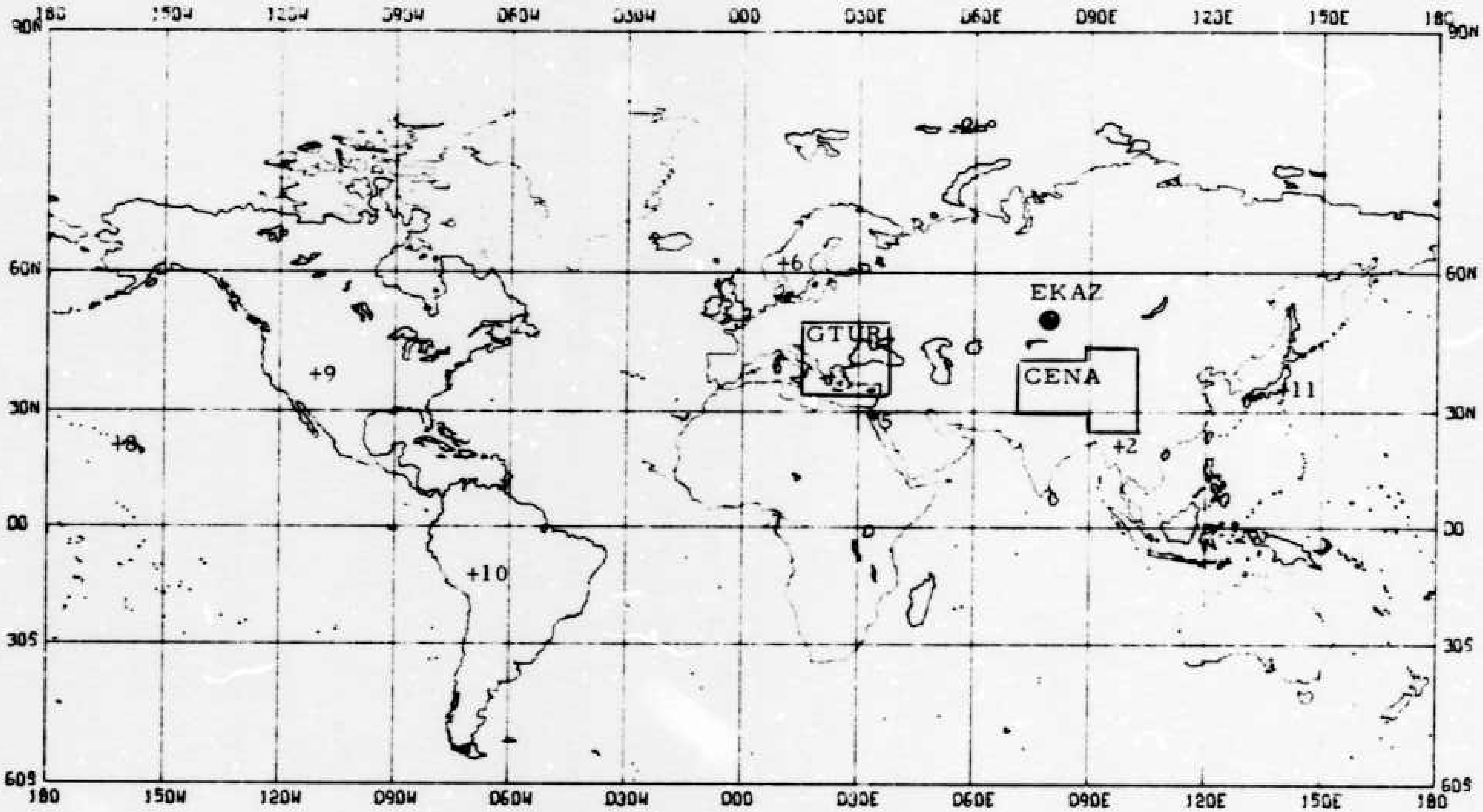
THE DATA BASE

## A. THE AREAS OF INTEREST

Three regions were initially selected for this evaluation of the CMF, RWMF, and TCA processor data enhancement techniques. These regions are the central Asia region (CENA), the Greece-Turkey region (GTUR), and the eastern Kazakh test region (EKAZ). These are shown in Figure II-1. The first two regions were selected to evaluate the application of the data enhancement technques to earthquakes, with the intent of investigating any differences in behavior of each technique due to source and path differences. The third region (EKAZ) was selected to evaluate the application of these techniques to presumed explosions. Unfortunately, this region yielded only ten presumed explosions, which is too small a data base to allow meaningful analysis. Therefore, eastern Kazakh presumed explosions are not included in this study. In future work, when sufficient data is available, events from this region will be investigated in terms of matched filters and the three-component adaptive processor.

## B. AVAILABLE DATA

A total of 53 earthquakes from central Asia and 28 earthquakes from Greece-Turkey were processed. The parameters for these events are listed in Tables II-1 and II-2, respectively. The event numbers (ENVO) are taken from Lambert et al., 1973. All events processed lie in the period 1 January 1973 to 15 March 1973. This time frame was chosen for the following reasons:

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MAP SCALE: 0.750 IN./ 30 DEG. LONGITUDE

FIGURE II-1

LOCATION OF STATIONS AND AREAS OF INTEREST

TABLE II-1

CENTRAL ASIA REGION EVENT PARAMETERS
(PAGE 1 OF 2)

| EVNO | MONTH | DAY | ORIGIN TIME | MB | LAT | LONG | OP STATIONS 2 | 5 | 6 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 881 | 1 | 2 | 22.25.57 | 5.2 | 31.2 | 88.1 | X | X | X | X | | | X |
| 884 | 1 | 3 | 14.31. 4 | 5.5 | 39.1 | 71.9 | X | X | X | X | X | | X |
| 885 | 1 | 3 | 15. 5.16 | 4.8 | 39.1 | 72.1 | X | X | X | X | X | | X |
| 886 | 1 | 3 | 17. 4.43 | 3.8 | 34.0 | 72.0 | X | X | X | X | X | | X |
| 887 | 1 | 3 | 20.36. 6 | 4.7 | 39.0 | 72.6 | X | X | | | | | X |
| 895 | 1 | 9 | 16.17.55 | 4.9 | 39.5 | 73.7 | X | X | X | | | | |
| 896 | 1 | 10 | 3. 2.32 | 4.8 | 32.6 | 68.3 | X | X | | X | | | |
| 900 | 1 | 11 | 4. 4.41 | 3.9 | 37.0 | 70.0 | X | X | X | | | | |
| 902 | 1 | 12 | 17.35.49 | 3.7 | 38.0 | 70.0 | X | X | X | | X | | X |
| 905 | 1 | 13 | 1.53.36 | 3.8 | 34.0 | 74.0 | | | X | | X | X | X |
| 908 | 1 | 15 | 12.55.44 | 5.1 | 40.4 | 91.1 | X | | X | X | X | | |
| 909 | 1 | 15 | 14.42. 7 | 4.7 | 40.4 | 91.1 | X | | X | X | | | |
| 910 | 1 | 15 | 18.48.43 | 3.8 | 36.1 | 73.4 | X | | X | X | X | | |
| 911 | 1 | 16 | 21.31.26 | 5.1 | 33.2 | 75.7 | X | | X | X | X | | |
| 913 | 1 | 16 | 23.38.39 | 3.7 | 33.0 | 76.0 | | | X | X | X | | |
| 914 | 1 | 18 | 6.47.28 | 4.6 | 34.9 | 99.6 | X | | X | X | X | | X |
| 915 | 1 | 18 | 11. 8.11 | 4.8 | 32.7 | 68.4 | X | | | X | X | X | X |
| 916 | 1 | 19 | 3.15.39 | 4.5 | 32.7 | 68.4 | | X | X | X | X | | |
| 918 | 1 | 19 | 15.10. 2 | 5.0 | 32.7 | 68.3 | X | X | X | X | X | X | X |
| 919 | 1 | 19 | 18.42.41 | 3.6 | 35.0 | 71.0 | X | | | X | X | X | X |
| 920 | 1 | 20 | 1.50.51 | 3.7 | 45.0 | 96.0 | X | X | | X | X | X | X |
| 922 | 1 | 20 | 14.31.54 | 4.0 | 31.0 | 67.0 | X | X | | X | X | | X |
| 924 | 1 | 21 | 3.23.53 | 4.3 | 41.0 | 71.0 | X | X | | X | X | X | X |
| 926 | 1 | 23 | 11.31.48 | 4.9 | 40.4 | 91.0 | X | | X | X | | X | X |
| 929 | 1 | 24 | 3.20.20 | 5.1 | 41.0 | 82.2 | X | | X | X | | X | X |
| 931 | 1 | 24 | 15.33.28 | 3.7 | 32.0 | 76.0 | X | X | X | X | | | X |
| 938 | 1 | 27 | 8.57.54 | 4.0 | 36.0 | 74.0 | X | X | X | X | | | X |
| 940 | 1 | 29 | 4.32. 6 | 5.0 | 35.8 | 73.3 | X | X | X | X | | | X |

TABLE II-1

CENTRAL ASIA REGION EVENT PARAMETERS
(PAGE 2 OF 2)

| EVNO | MONTH | DAY | ORIGIN TIME | MB | LAT | LONG | OP STATIONS 2 | 5 | 6 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 946 | 1 | 30 | 11.10.12 | 4.3 | 42.7 | 94.3 | X | X | X | X | | | X |
| 950 | 2 | 16 | 7.29.47 | 4.9 | 31.7 | 100.0 | | | X | X | X | | |
| 952 | 2 | 17 | 4.21.25 | 3.7 | 33.0 | 96.0 | | | X | X | X | | |
| 953 | 2 | 17 | 6.15.48 | 3.6 | 27.0 | 95.0 | | | X | | | | |
| 954 | 2 | 18 | 21.39. 2 | 4.9 | 40.8 | 74.1 | | | X | | X | | |
| 955 | 2 | 19 | 17.34.45 | 4.2 | 32.0 | 88.0 | | | X | X | X | | |
| 958 | 2 | 20 | 14.31.41 | 3.9 | 35.0 | 72.0 | | | X | X | X | | |
| 961 | 2 | 22 | 18.18. 5 | 4.3 | 38.7 | 98.7 | | | X | X | X | | X |
| 965 | 2 | 23 | 10.45. 6 | 4.8 | 37.6 | 86.4 | | | X | X | X | | X |
| 978 | 2 | 26 | 20.11. 4 | 4.2 | 33.0 | 91.0 | | X | X | | X | | |
| 1017 | 3 | 1 | 12.59.42 | 4.2 | 42.0 | 97.0 | | | X | | X | | X |
| 1033 | 3 | 3 | 10.22.46 | 4.6 | 40.2 | 78.8 | | X | X | X | X | | X |
| 1034 | 3 | 3 | 23.47.18 | 3.7 | 34.0 | 74.0 | | X | X | X | X | | X |
| 1044 | 3 | 5 | 21.21.17 | 3.4 | 40.0 | 76.0 | | | X | | X | | X |
| 1047 | 3 | 6 | 3.30.41 | 3.6 | 36.0 | 73.0 | | X | | | X | | |
| 1049 | 3 | 6 | 18. 9.52 | 3.6 | 35.0 | 72.0 | | X | X | | | | |
| 1051 | 3 | 6 | 19.11.24 | 3.6 | 36.0 | 78.0 | | | X | | | | X |
| 1053 | 3 | 7 | 7. 7.38 | 5.0 | 36.4 | 71.5 | | | X | | X | | X |
| 1063 | 3 | 9 | 6. 9.17 | 4.0 | 34.0 | 68.0 | X | | X | | X | | X |
| 1064 | 3 | 9 | 11.45. 0 | 3.8 | 48.0 | 97.0 | X | | X | | | | X |
| 1067 | 3 | 9 | 16.51.35 | 3.5 | 36.0 | 71.0 | | | X | | X | | X |
| 1069 | 3 | 9 | 21.35. 8 | 3.8 | 25.0 | 92.0 | | | X | | X | | X |
| 1084 | 3 | 12 | 14.21.29 | 4.5 | 38.4 | 93.5 | X | X | X | X | X | | X |
| 1091 | 3 | 15 | 21.12.26 | 3.7 | 28.0 | 93.0 | X | | X | | X | | X |
| 1092 | 3 | 15 | 23.24.32 | 4.2 | 38.0 | 77.0 | X | | | | X | | X |

TABLE II-2

GREECE-TURKEY REGION EVENT PARAMETERS

| EVNO | MONTH | DAY | ORIGIN TIME | MB | LAT | LONG | OP STATIONS 2 | 5 | 6 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 890 | 1 | 5 | 5.49.17 | 5.3 | 35.8 | 21.8 | X | X | X | X | X | | X |
| 891 | 1 | 5 | 7.28.23 | 4.0 | 35.0 | 22.0 | X | X | X | X | X | | X |
| 892 | 1 | 5 | 19.12.12 | 4.3 | 35.6 | 21.9 | X | X | | X | X | | X |
| 897 | 1 | 10 | 3.24.11 | 5.0 | 37.8 | 21.3 | X | X | X | X | X | X | |
| 912 | 1 | 16 | 22.45.16 | 4.5 | 35.1 | 22.6 | | | X | | X | X | |
| 927 | 1 | 23 | 11.46.42 | 4.6 | 34.3 | 25.1 | X | | X | X | | X | X |
| 933 | 1 | 26 | 7.50.18 | 4.7 | 37.0 | 19.0 | | X | X | X | | | |
| 934 | 1 | 26 | 12.23. 4 | 3.7 | 35.0 | 24.0 | X | | | | | | X |
| 939 | 1 | 28 | 20.35.55 | 4.3 | 38.2 | 19.5 | X | X | | | | | X |
| 941 | 1 | 29 | 6. 2.32 | 4.3 | 38.2 | 19.9 | X | X | X | | | | |
| 944 | 1 | 30 | 5.41.44 | 3.9 | 38.7 | 26.2 | X | X | X | X | | | X |
| 945 | 1 | 30 | 5.50.39 | 3.6 | 38.0 | 23.0 | X | X | X | X | | | X |
| 947 | 1 | 30 | 12. 1. 9 | 3.3 | 39.6 | 23.8 | X | X | X | X | | | X |
| 956 | 2 | 19 | 18.10.10 | 4.5 | 40.2 | 33.9 | | | X | X | X | | |
| 957 | 2 | 20 | 5.55.14 | 4.5 | 34.4 | 23.8 | | | X | | | | X |
| 968 | 2 | 24 | 23.54. 3 | 4.1 | 35.0 | 24.5 | | | X | | | | |
| 971 | 2 | 25 | 12.55.21 | 3.5 | 37.7 | 21.0 | | X | | X | | | |
| 972 | 2 | 25 | 14.55.21 | 4.1 | 38.8 | 29.4 | | | X | X | | | |
| 983 | 2 | 27 | 17.10.11 | 4.2 | 38.9 | 29.9 | | X | X | | X | | |
| 1021 | 3 | 2 | 2.45.21 | 3.9 | 34.0 | 25.0 | | X | | | X | | |
| 1028 | 3 | 2 | 19.30. 1 | 3.6 | 39.3 | 27.6 | | X | X | X | | | |
| 1042 | 3 | 5 | 15.40.33 | 3.7 | 38.7 | 20.2 | | X | X | | | | X |
| 1048 | 3 | 6 | 12.21.33 | 4.0 | 38.7 | 23.6 | | X | | | X | | X |
| 1052 | 3 | 7 | 6.35.10 | 3.6 | 41.7 | 20.0 | | X | X | | X | | X |
| 1073 | 3 | 10 | 11.30. 6 | 3.7 | 35.0 | 23.0 | X | X | X | | X | | |
| 1081 | 3 | 12 | 8.31.14 | 4.4 | 37.5 | 29.9 | X | X | | | X | | X |
| 1086 | 3 | 12 | 20.30.43 | 4.7 | 35.9 | 21.7 | X | | | | X | | X |
| 1087 | 3 | 13 | 22.10.13 | 4.0 | 34.0 | 24.0 | X | X | X | | X | | X |

- It contained sufficient events from the selected regions to allow a meaningful analysis.
- A large number of stations were operational during this period.
- The amount of data to be processed was not so great as to preclude completion in the time allotted to the task.

The stations used in this analysis were CHG (2), EIL (5), KON (6), KIP (8), ALQ (9), ZLP (10), and MAT (11). These are shown on Figure II-1. Operational stations are indicated by an X in Tables II-1 and II-2. The remaining stations were not included because they either were not operational during the time period chosen or failed to record any events suitable for use as reference waveform matched filters. (It was desired that the entire data base be processed by each of the three techniques. This could not be done if a reference waveform matched filter was not available for each station.)

In order to evaluate the dB SNNR improvements of each data enhancement technique, each event as recorded at a given station was considered to be an individual event and is hereafter referred to as a station-event. The reason for this designation is that the travel paths and epicentral distances to each station are independent of each other. Thus, a chirp or reference waveform matched filter suitable for an event recorded at one station will not be of value for that same event recorded at a second station. This manner of considering the data yields a data base of 212 station-events from CENA and 101 station-events from GTUR.

In order to make comparisons with data reported previously, the detection levels were computed in terms of a network, using events rather than station-events. The configuration of available stations conforms most closely with those used for Network 3 (Lambert et al., 1973). The two

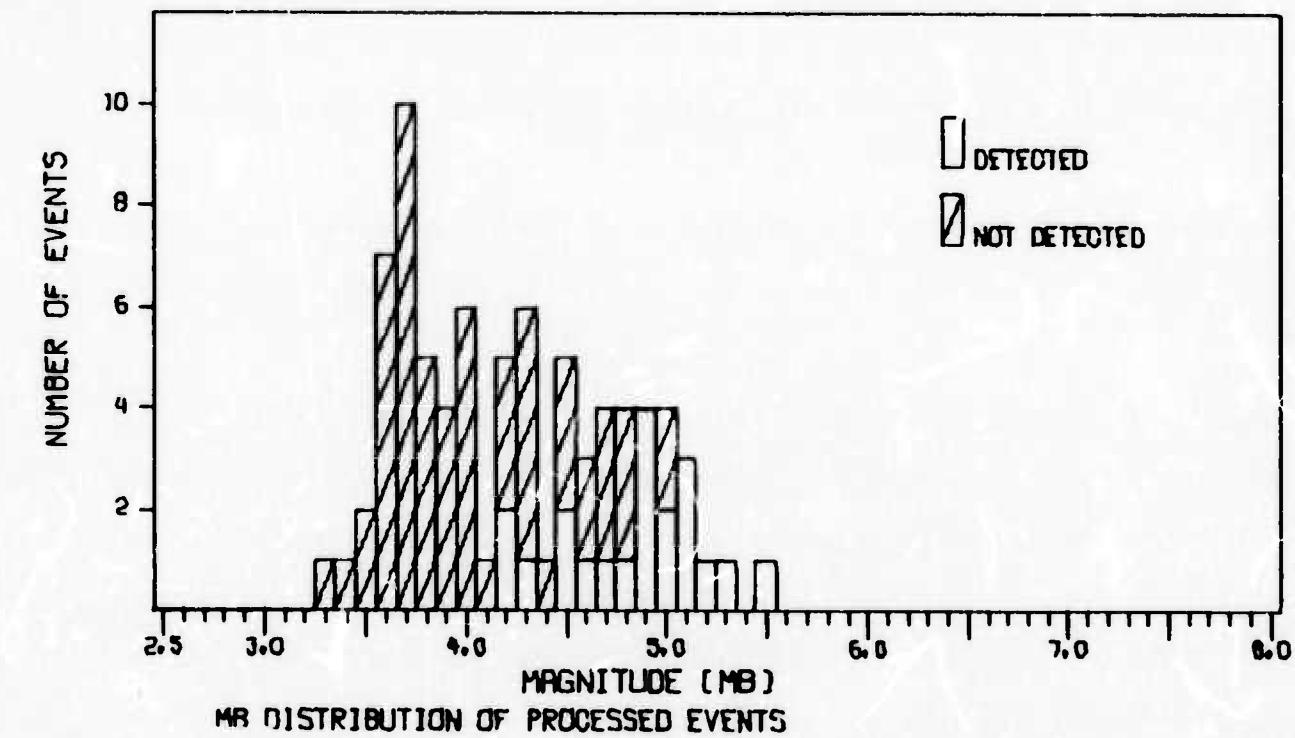
seismic regions were combined for this phase of the study to form a subset of the data base used to evaluate Network 3. To decrease the possibility of false alarms, an event was considered to be detected only if it was detected at two or more stations. By requiring two or more stations to be operational, a data base of 79 events was available for detection level computations.

The bodywave magnitude distribution and maximum-likelihood detection capability curve (Ringdal, 1974) are given by Figure II-2 for this combined region. This figure shows that for this region and the network, the 50 percent bandpass detection level is 4.72* and the 90 percent bandpass detection level is 5.25 $m_b$ units. We note that Network 3 had a 50 percent bandpass detection level of 4.50 and a 90 percent bandpass detection level of 4.99 $m_b$ units for the case where detections on at least two stations were required. The difference in detection level between the two networks is attributed to the fact that the data for Network 3 was derived from a much larger region than was the data for the network under consideration.

## C. DATA QUALITY AND DETECTION CRITERIA

All station-events initially proposed for analysis by the three data enhancement techniques were first screened for mixing and instrument malfunctions. All mixed station-events were rejected. If only one component of a station-event contained a malfunction, it was accepted as part of the data base, since it could still be used in the matched filter detection studies. If more than one component contained a malfunction, the station-event was

*Throughout this report, two decimal places will be used when discussing detection levels and $M_s$ meansurements in order to maintain the convention of earlier reports. It is recognized that the degree of accuracy in such measurements actually permits only one decimal place.



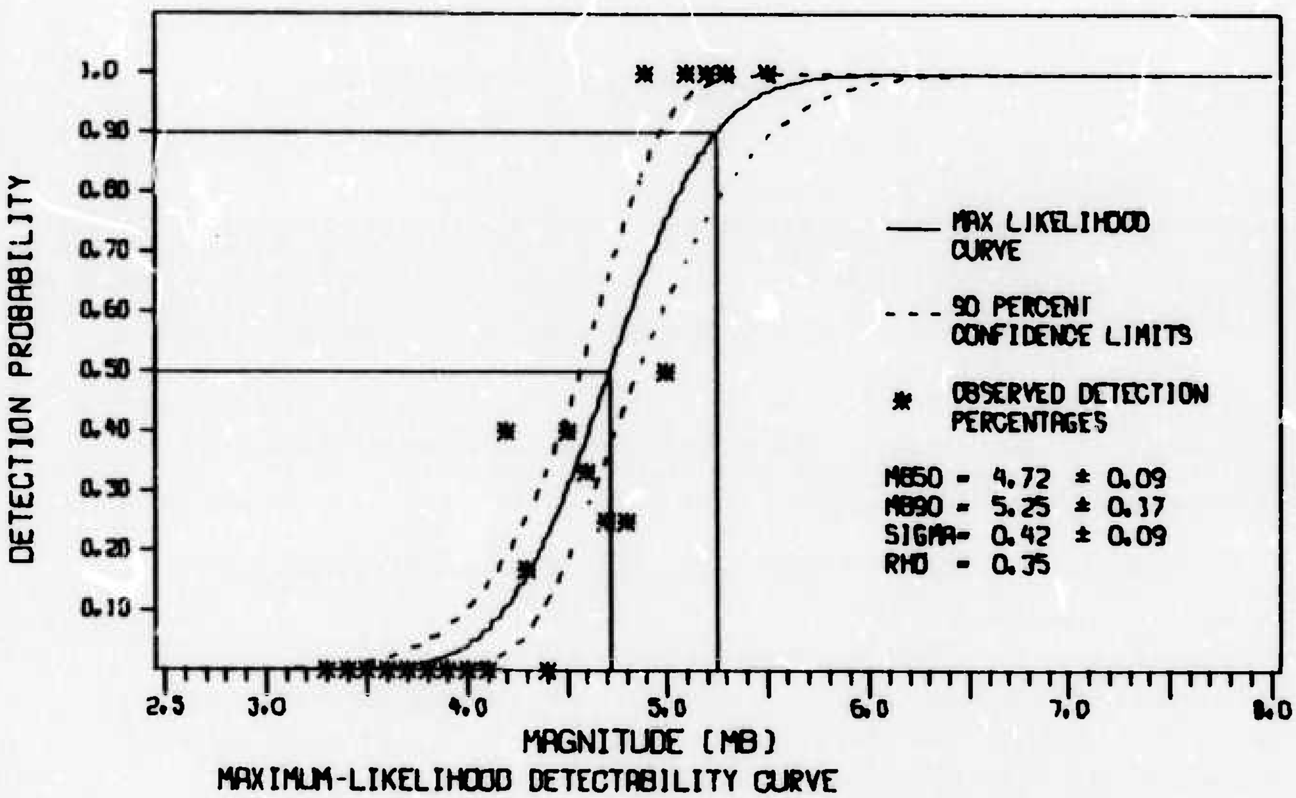




FIGURE II-2

DETECTION STATISTICS FOR THE COMBINED REGION

rejected. The results of this screening process are given in Tables II-1 and II-2, where an X under a station number indicates that particular station-event was included in the analysis.

Lambert et al., (1973) reported that erratic static gains were encountered from time to time on the horizontal components at virtually all stations. Therefore, SNNR improvements and surface-wave magnitude values were calculated only for the vertical component data. The horizontal data was, however, included in the detection statistics.

The criteria for determining whether a detection was achieved with the use of any of the three enhancement techniques of a station-event are:

- A peak appeared on the matched filter or TCA processor response trace 3 dB above any other peak in the first half of the signal gate defined by the estimated arrival time and the Rayleigh duration time.
- A station-event was listed as a detection if it was detected on either the vertical (Rayleigh wave) or transverse (Love wave) components.
- An event was considered to be detected if it was detected at two or more stations.

## SECTION III

## CHIRP MATCHED FILTER EVALUATION

### A. DISCUSSION

Linear chirp matched filters were applied to all the station - events listed in Tables II-1 and II-2. The chirp filters were specified and applied in the frequency domain, using a chirp bandpass of 0.023 to 0.059 Hz. Chirp filter application was performed by Fourier transforming the data trace to the frequency domain and performing cross-correlation. After application of the filters, the data were inverse-transformed to obtain time-domain chirp filter outputs.

The chirp filter response function is:

$$G(K) = \begin{cases} e^{i2\pi(C/N)(K-K_o)^2} & \text{if } K_L \leq K \leq K_H \\ 0 & \text{if } 0 \leq K \leq K_L \text{ or } K_H \leq K \leq N/2 \end{cases}$$

$$G(-K) = G(K)^*$$

where:

$K$ = the discrete Fourier transform frequency index,

$K_L$ and $K_H$ = the lowest and highest frequencies in the passband,

$K_o$ = the frequency index at which zero phase shift occurs,

$N$ = the number of transform points,

$C$ = a parameter which controls the length of the corresponding time-domain waveform.

$G(K)^*$ = complex conjugate of $G(K)$

This yields a dispersive time-domain chirp waveform with a linear group delay and essentially flat amplitude at all periods in the band corresponding to $K_L \leq K \leq K_N$ (Harley, 1971).

To minimize computer and Calcomp plotter usage, it was necessary to obtain some idea of optimum chirp length in terms of event epicenter-station separation. Therefore, the following procedure was carried out for the two seismic regions.

First, a subset of the data base for each region was formed, consisting of all station-events detected on the bandpass-filtered trace Chirp filters, ranging in length from 50 seconds to 1250 seconds for events closer than $60^o$, and from 300 seconds to 1500 seconds for events farther than $60^o$, with length increment of 50 seconds, were applied to each station-event in the subset. The time trace having the highest peak value of each sequence of chirp filter responses, as picked from the computer print-out, was then plotted to ensure that it was in fact a detection. Plots of chirp length versus epicentral distance were then made, using the length associated with the highest peak value. A least-mean-square fit was then made to the data. This produced an estimate of the optimum chirp length in terms of epicentral distance.

Next, the chirp length increments were set as listed in Table III-1. The reason for changing the length increment with increasing epicentral distance is that if a constant increment were used, it could form too course a "grid" for close events, with the result that the optimum chirp length would be missed. For distant events, this same increment could form too fine a "grid," resulting in wasted computer and plotter time. The chosen chirp length increments were selected in an effort to minimize this problem.

TABLE III-1

CHIRP FILTER BOUNDS AND INCREMENTS

| Epicentral Distance | Increment | Lower Bound* | Upper Bound* |
|---|---|---|---|
| $< 25^{\circ}$ | 25 sec | -150 sec | + 150 sec |
| $25^{\circ}$-$40^{\circ}$ | 40 sec | -150 sec | +150 sec |
| $40^{\circ}$-$60^{\circ}$ | 50 sec | -200 sec | + 200 sec |
| $60^{\circ}$-$80^{\circ}$ | 75 sec | -300 sec | + 300 sec |
| $> 80^{\circ}$ | 100 sec | -300 sec | + 400 sec |

*The bounds are given in seconds below (minus) or seconds above (plus) the least-mean-square fit to the data.

Finally, upper and lower limits in the range of chirp lengths were selected. These are listed in Table III-1.

The bounds were set so that at least 85 percent of the optimum chirp lengths of the LR-V data (as determined from the detected-on-bandpass data subsets) lay between them.

Using the above information, chirp matched filters were next applied to those station-events which were not detected on the bandpass filtered trace. This was performed in a two-pass operation. For the first pass, a suite of chirps was generated using the appropriate increment and set of bounds. The highest peak amplitude of the chirp responses in the appropriate time gate was picked from the computer print-out. For the second pass, the chirp length corresponding to this peak was used as the center length of a set of three chirps, again separated in length by the appropriate time increment. The chirp responses so obtained were then plotted and picked for detections and chirp response amplitudes. The chirp length versus epicentral distance data points so obtained are plotted in Figures III-1, III-2, III-3, and III-4, as solid circles. In these figures, the data obtained from station-events detected on the bandpass filter are denoted by open circles. The least-mean-square-error fit shown was made on the data points represented by open circles.

## B. CHIRP MATCHED FILTER RESULTS

The points to be considered in the evaluation of chirp matched filters are dB SNNR improvements, detection level improvements, and surface-wave magnitudes derived from the filter responses. These will be discussed in terms of data from the two regions.

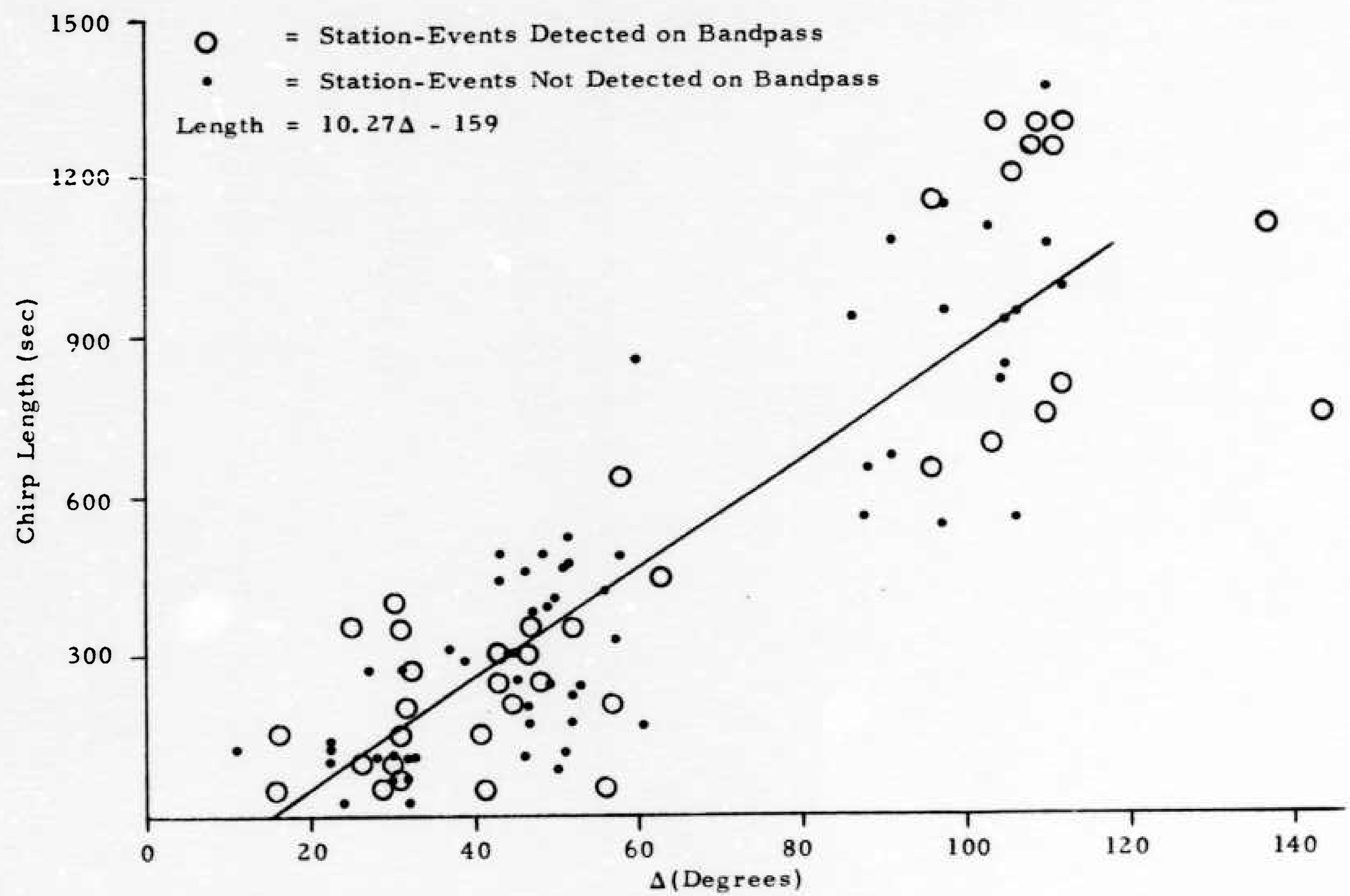



FIGURE III-1

CHIRP LENGTH VERSUS DISTANCE - CENTRAL ASIA - LR-V

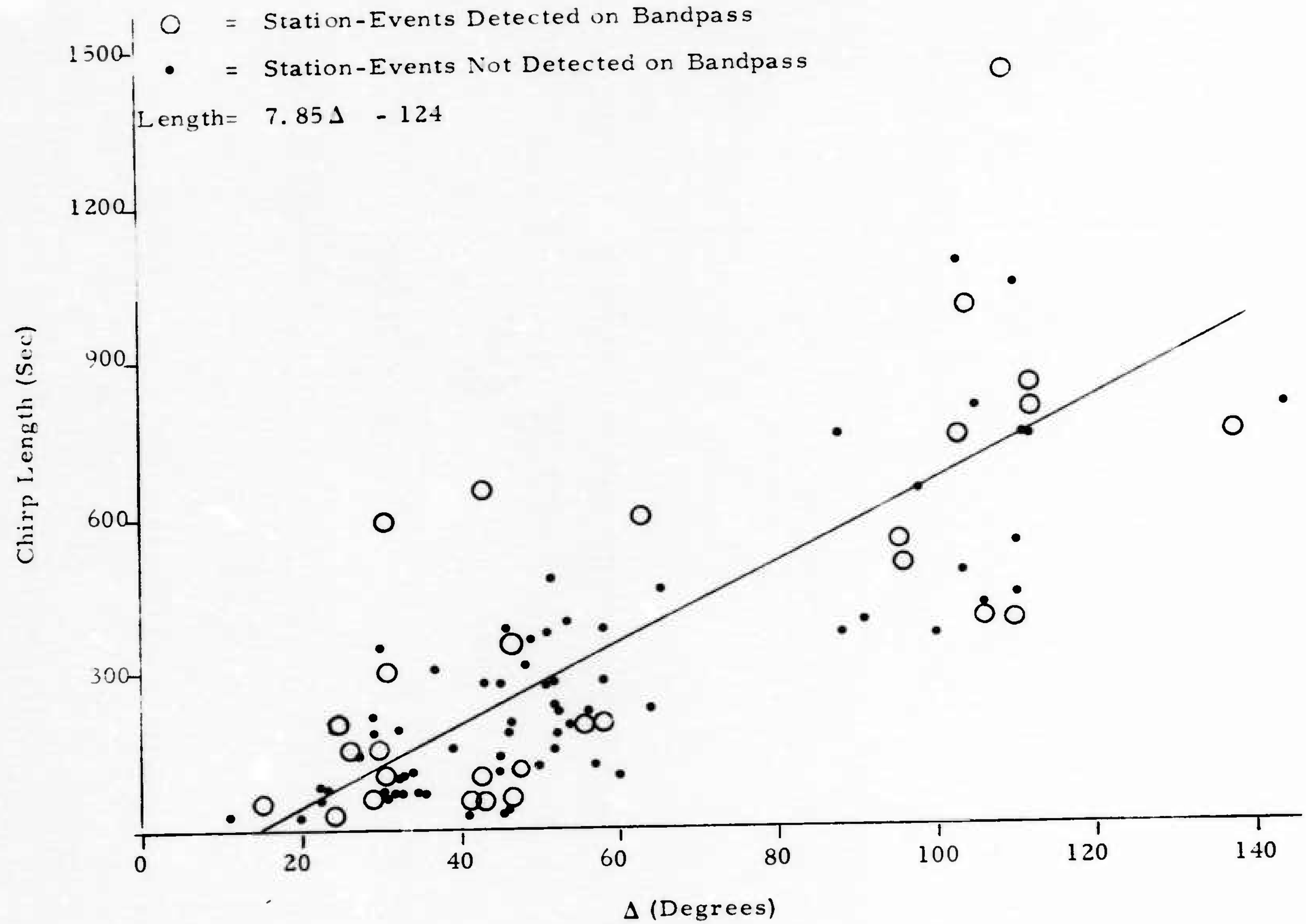



FIGURE III-2

CHIRP LENGTH VERSUS DISTANCE - CENTRAL ASIA - LQ - T

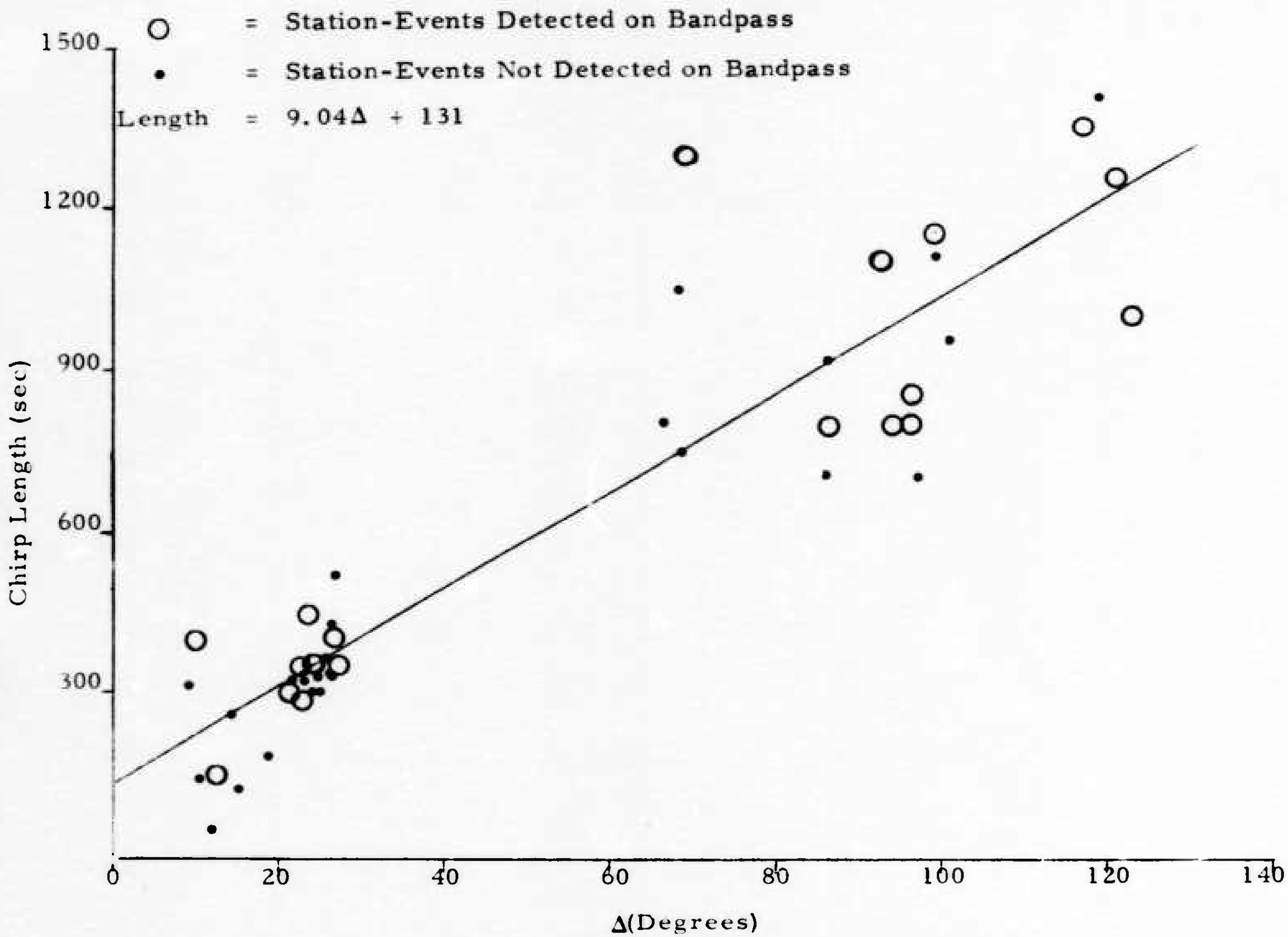



FIGURE III-3

CHIRP LENGTH VERSUS DISTANCE - GREECE-TURKEY-LR-V

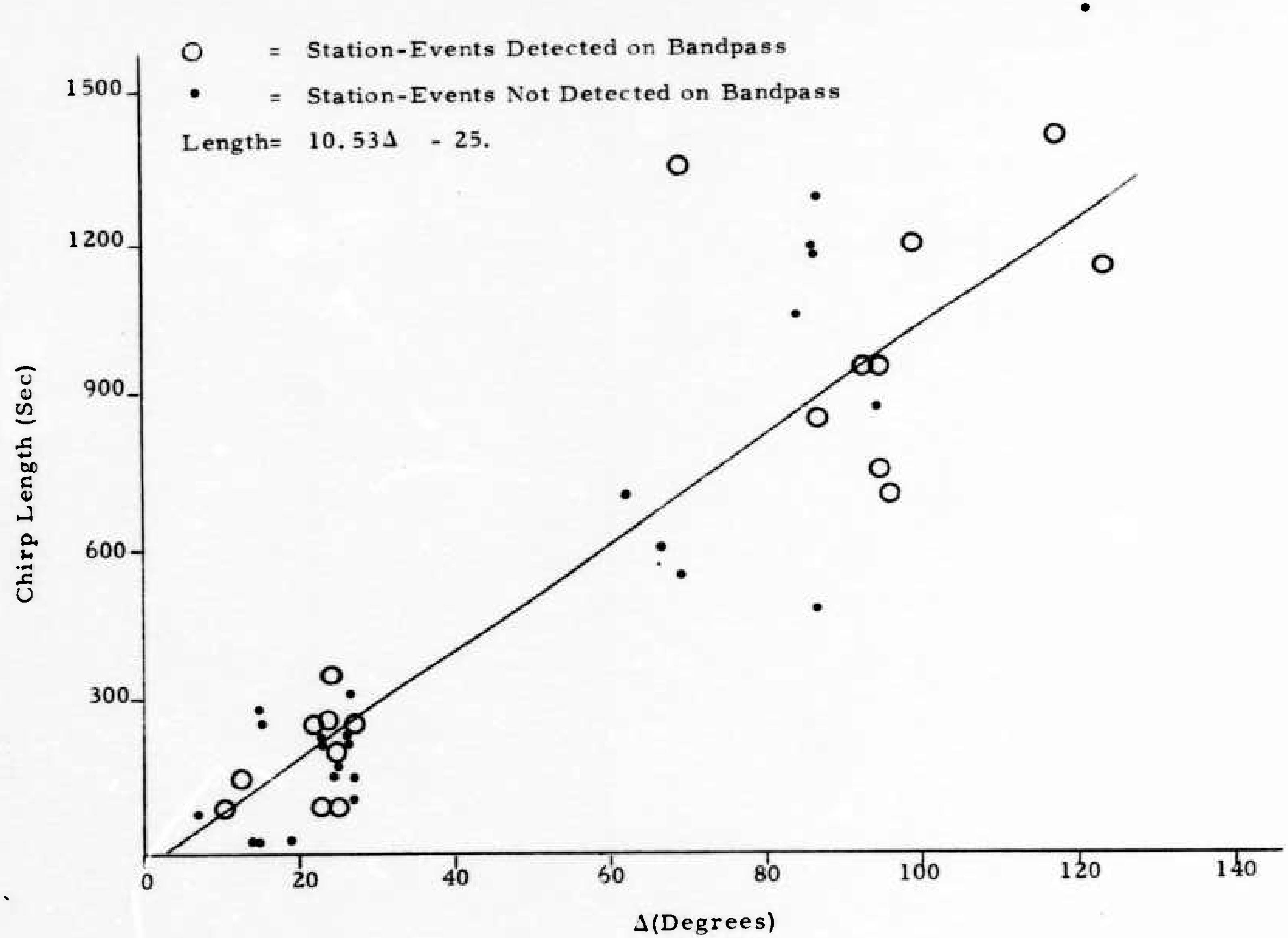



FIGURE III-4

CHIRP LENGTH VERSUS DISTANCE - GREECE - TURKEY - LQ - T

1. dB SNNR Improvements

The dB SNNR improvement of the chirp matched filter over the equivalent (0.023-0.059 Hz) bandpass filter was calculated by the formula given in Section 1-C. SNNR improvements were computed for every station-event detected on the bandpass filter response. The results are listed in Table III-2 for the central Asia region and Table III-3 for the Greece-Turkey region.

Considering those stations which detected four or more test events, the following comments on chirp matched filter results can be made. (The term "poor" indicates a mean SNNR improvement of less than 1 dB, "fair" a mean between 1 and 2 dB, "good" a mean between 2 and 4 dB, and "excellent" a mean greater than 4 dB.)

- Station 2 - SNNR improvements were fair for test events from CENA.
- Station 5 - SNNR improvements were good for test events from CENA and fair for test events from GTUR.
- Station 6 - SNNR improvements were fair for test events from CENA and good for test events from GTUR.
- Station 8 - SNNR improvements were good for test events from CENA.
- Station 9 - SNNR improvements were excellent for test events from GTUR.
- Station 11 - SNNR improvements were fair for test events from CENA.

TABLE III-2

CMF SNNR IMPROVEMENTS FOR CENTRAL ASIA EVENTS
(LR-V)
(PAGE 1 OF 3)

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 881 | 2 | -0.4 |
| 884 | 2 | 1.5 |
| 895 | 2 | 1.5 |
| 908 | 2 | 1.7 |
| 909 | 2 | 2.0 |
| 911 | 2 | 4.7 |
| 914 | 2 | 1.1 |
| 915 | 2 | 1.1 |
| 918 | 2 | 1.5 |
| 926 | 2 | 1.2 |
| 929 | 2 | 1.9 |
| 946 | 2 | 0.7 |
| 1091 | 2 | 4.8 |
| 1092 | 2 | 2.2 |

MEAN SNNR IMPROVEMENT= 1.82

STANDARD DEVIATION= 1.39

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 881 | 5 | 1.2 |
| 884 | 5 | 1.8 |
| 918 | 5 | 1.7 |
| 978 | 5 | 3.6 |

MEAN SNNR IMPROVEMENT= 2.07

STANDARD DEVIATION= 1.05

TABLE III-2

CMF SNNR IMPROVEMENTS FOR CENTRAL ASIA EVENTS
(LR-V)
(PAGE 2 OF 3)

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 881 | 6 | 2.8 |
| 884 | 6 | 3.3 |
| 895 | 6 | 2.4 |
| 908 | 6 | 0.5 |
| 911 | 6 | 1.6 |
| 916 | 6 | 4.5 |
| 918 | 6 | 2.7 |
| 926 | 6 | -0.5 |
| 929 | 6 | 1.5 |
| 950 | 6 | 3.1 |
| 952 | 6 | 2.9 |
| 954 | 6 | 2.7 |
| 955 | 6 | -0.1 |
| 965 | 6 | 1.6 |
| 978 | 6 | 1.4 |

MEAN SNNR IMPROVEMENT= 2.03

STANDARD DEVIATION= 1.35

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 881 | 8 | 1.6 |
| 884 | 8 | 3.4 |
| 908 | 8 | 2.6 |
| 911 | 8 | 4.9 |
| 918 | 8 | 6.9 |
| 929 | 8 | 4.1 |
| 946 | 8 | 2.1 |
| 950 | 8 | 5.8 |
| 965 | 8 | -0.4 |

MEAN SNNR IMPROVEMENT= 3.44

STANDARD DEVIATION= 2.26

TABLE III-2

CMF SNNR IMPROVEMENTS FOR CENTRAL ASIA EVENTS
(LR-V)
(PAGE 3 OF 3)

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 884 | 9 | 6.9 |
| 908 | 9 | 1.5 |
| 911 | 9 | 9.4 |
| 916 | 9 | 2.7 |
| 918 | 9 | 6.3 |
| 950 | 9 | 2.5 |
| 954 | 9 | 7.8 |
| 965 | 9 | 5.8 |
| 978 | 9 | 6.0 |

MEAN SNNR IMPROVEMENT= 5.43

STANDARD DEVIATION= 2.65

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 918 | 10 | 4.3 |
| 929 | 10 | 2.8 |

MEAN SNNR IMPROVEMENT= 3.55

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 881 | 11 | 0.2 |
| 884 | 11 | 1.9 |
| 914 | 11 | 3.8 |
| 918 | 11 | 0.6 |
| 926 | 11 | 0.8 |
| 929 | 11 | 1.2 |
| 946 | 11 | -0.6 |
| 961 | 11 | 2.4 |
| 965 | 11 | 1.7 |
| 1044 | 11 | -2.7 |
| 1069 | 11 | 2.8 |

MEAN SNNR IMPROVEMENT= 1.10

STANDARD DEVIATION= 1.77

TABLE III-3

CMF SNNR IMPROVEMENTS FOR GREECE-TURKEY EVENTS
(LR-V)
(PAGE 1 OF 2)

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 890 | 2 | 4.2 |

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 890 | 5 | 1.0 |
| 933 | 5 | 1.0 |
| 971 | 5 | 2.7 |
| 983 | 5 | 2.5 |
| 1081 | 5 | 0.4 |

MEAN SNNR IMPROVEMENT= 1.52

STANDARD DEVIATION= 1.02

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 890 | 6 | 2.1 |
| 897 | 6 | 7.0 |
| 927 | 6 | 0.5 |
| 933 | 6 | 3.0 |
| 941 | 6 | 4.8 |
| 956 | 6 | 5.2 |
| 957 | 6 | 3.7 |
| 968 | 6 | 1.3 |
| 972 | 6 | 3.3 |
| 983 | 6 | 2.8 |
| 1028 | 6 | 2.3 |
| 1052 | 6 | 3.2 |

MEAN SNNR IMPROVEMENT= 3.27

STANDARD DEVIATION= 1.77

TABLE III-3

CMF SNNR IMPROVEMENTS FOR GREECE-TURKEY EVENTS
(LR-V)
(PAGE 2 OF 2)

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 890 | 8 | 6.3 |
| 897 | 8 | 6.6 |
| 956 | 8 | 5.4 |

MEAN SNNR IMPROVEMENT= 6.10

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 890 | 9 | 1.4 |
| 897 | 9 | 2.3 |
| 956 | 9 | 3.6 |
| 983 | 9 | 4.7 |

MEAN SNNR IMPROVEMENT= 3.00

STANDARD DEVIATION= 1.45

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 897 | 10 | 7.0 |

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 890 | 11 | 3.9 |

It is immediately obvious that more data is needed from the Greece-Turkey region since it is possible to compare the SNNR improvements for the two regions at only three stations. At station 5, the mean SNNR improvement for CENA is higher than the mean SNNR improvement for GTUR. At station 6, the SNNR improvements for GTUR test events have a higher mean value than do those for CENA test events. At station 9, the SNNR improvements for CENA test events have a higher mean value than do those for GTUR test events.

The standard deviation values for each of the mean SNNR improvements indicate there is considerable variation in the SNNR improvements yielded by chirp matched filters. For example, the SNNR improvement values for test events from central Asia as recorded at station 8 range from -0.4 dB to 6.9 dB. This range in values may be due to different source mechanisms, since we note that the SNNR improvements can be divided roughly into two groups, one of low SNNR improvements and one of high SNNR improvements. Given a sufficiently large data base, we may be able to determine mean SNNR improvements for sub-regions which will have low standard deviations.

2. Surface Wave Detection Using Chirp Matched Filters

Using the detection criteria given in Section II-C, the detection capability of chirp matched filters was evaluated for the central Asia region, the Greece-Turkey region, and the combined central Asia-Greece-Turkey region. This evaluation was performed in terms of seismic events and the VLPE network. The results are as follows:

- CENA - Fifteen events were detected on the bandpass filter response. An additional 18 events were detected on the chirp matched filter response, resulting in a 120 percent increase in the number of events detected.

- GTUR - Five events were detected on the bandpass filter response. An additional 8 events were detected on the chirp matched filter response, resulting in a 160 percent increase in the number of events detected.

- Combined CENA and GTUR - Twenty events were detected on the bandpass filter response. An additional 26 events were detected on the chirp matched filter response, resulting in a 130 percent increase in the number of events detected.

Although the percentage increase in the number of events detected differs for the two regions, we note that in either case the number of detections is more than doubled by the use of chirp matched filters.

The detection capability of chirp matched filters in a network sense is illustrated by Figure III-5, which shows the bodywave magnitude distribution and maximum-likelihood detectability curve for the combined central Asia and Greece-Turkey region. Comparing this figure with the corresponding bandpass filter maximum-likelihood detectability curve of Figure II-2, we find that the use of chirp matched filters lowered the 50 percent detection level from 4.72 to 4.04 $m_b$ units and the 90 percent detection level from 5.25 to 4.90 $m_b$ units.

3. Surface-Wave Magnitude From Chirp Matched Filter Data

Surface-wave magnitudes were computed from chirp matched filter data using the equation:

$$M_s = LOG_{10}\left(\frac{A}{30}\right) - \frac{dB}{20} + LOG_{10}(DELTA) + 1.12$$

This is the same as the equation used to compute $M_s$ from bandpass-filtered data except that here the period is assumed to be 30 seconds, since no period can be measured from a matched filter response. The term $\frac{dB}{20}$ is subtracted

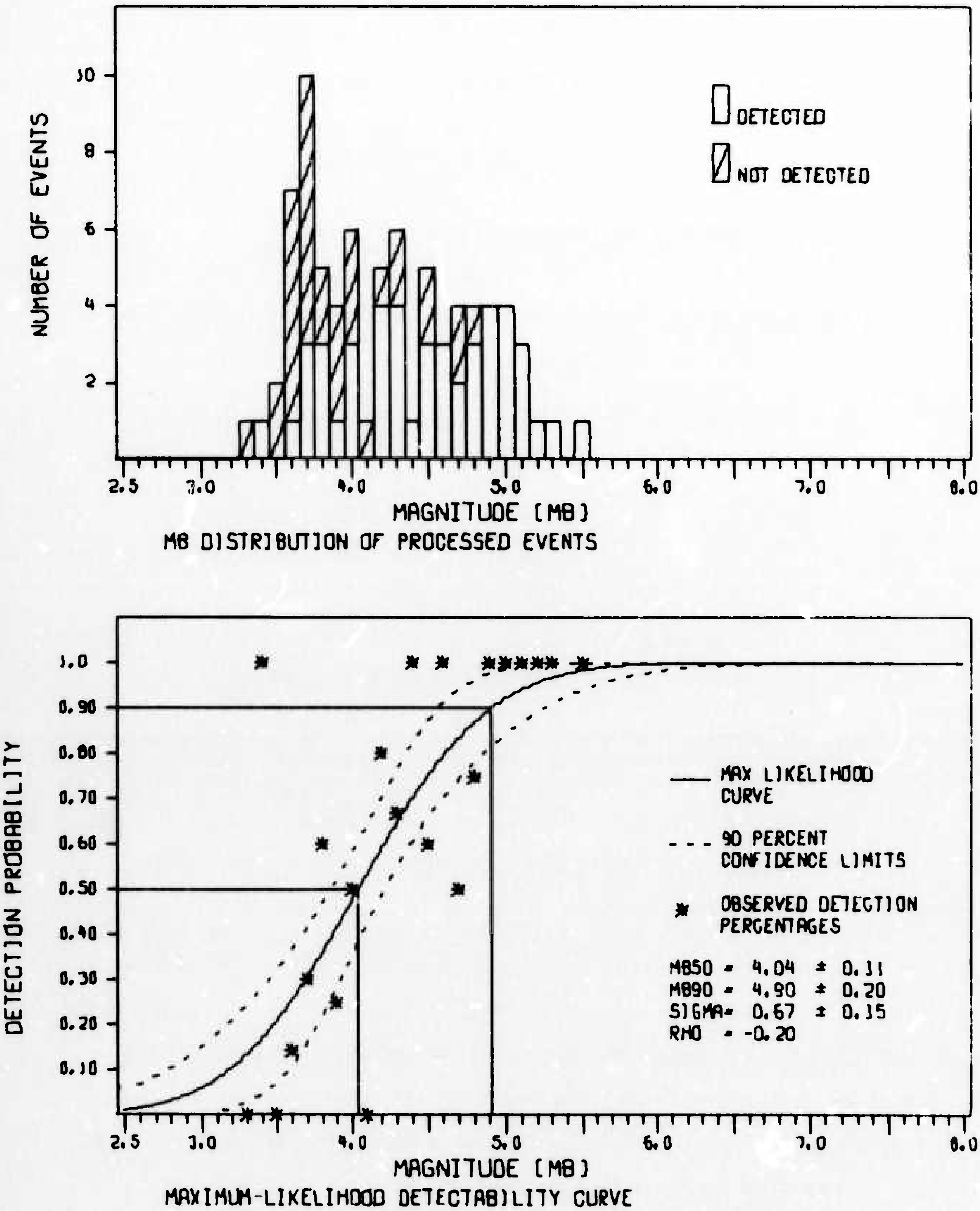



FIGURE III-5

DETECTION STATISTICS FOR THE COMBINED REGION - CMF DETECTIONS

to remove the SNNR improvement due to the matched filter. Since the period is assumed to be the instrument response peak, no instrument gain correction is needed (the instrument response is flat between 30 seconds and 40 seconds).

When SNNR improvement values were available for four or more events recorded at a station, the mean of those values was used in the surface-wave magnitude calculation. When less than four values were available, the overall average SNNR improvement was used.

From Tables III-2 and III-3, the SNNR improvement used were:

| Station | SNNR Improvements | |
|---|---|---|
| | CENA | GTUR |
| 2 | 1.8 | 3.4* |
| 5 | 2.1 | 1.5 |
| 6 | 2.0 | 3.3 |
| 8 | 3.4 | 3.4* |
| 9 | 5.4 | 3.0 |
| 10 | 2.6* | 3.4* |
| 11 | 1.1 | 3.4* |

where all values are in dB. An asterisk denotes the use of the overall average SNNR improvement value.

For station-events not detected on the bandpass filter response, the surface-wave magnitude values calculated using the above SNNR improvements are shown in Figure III-6. When $M_s$ values were computed at two or more stations for a given event, they were averaged to reduce the variance. The resulting plot shows network average $M_s$ values with one or more stations reporting. The solid line is a best linear fit to the data, computed by

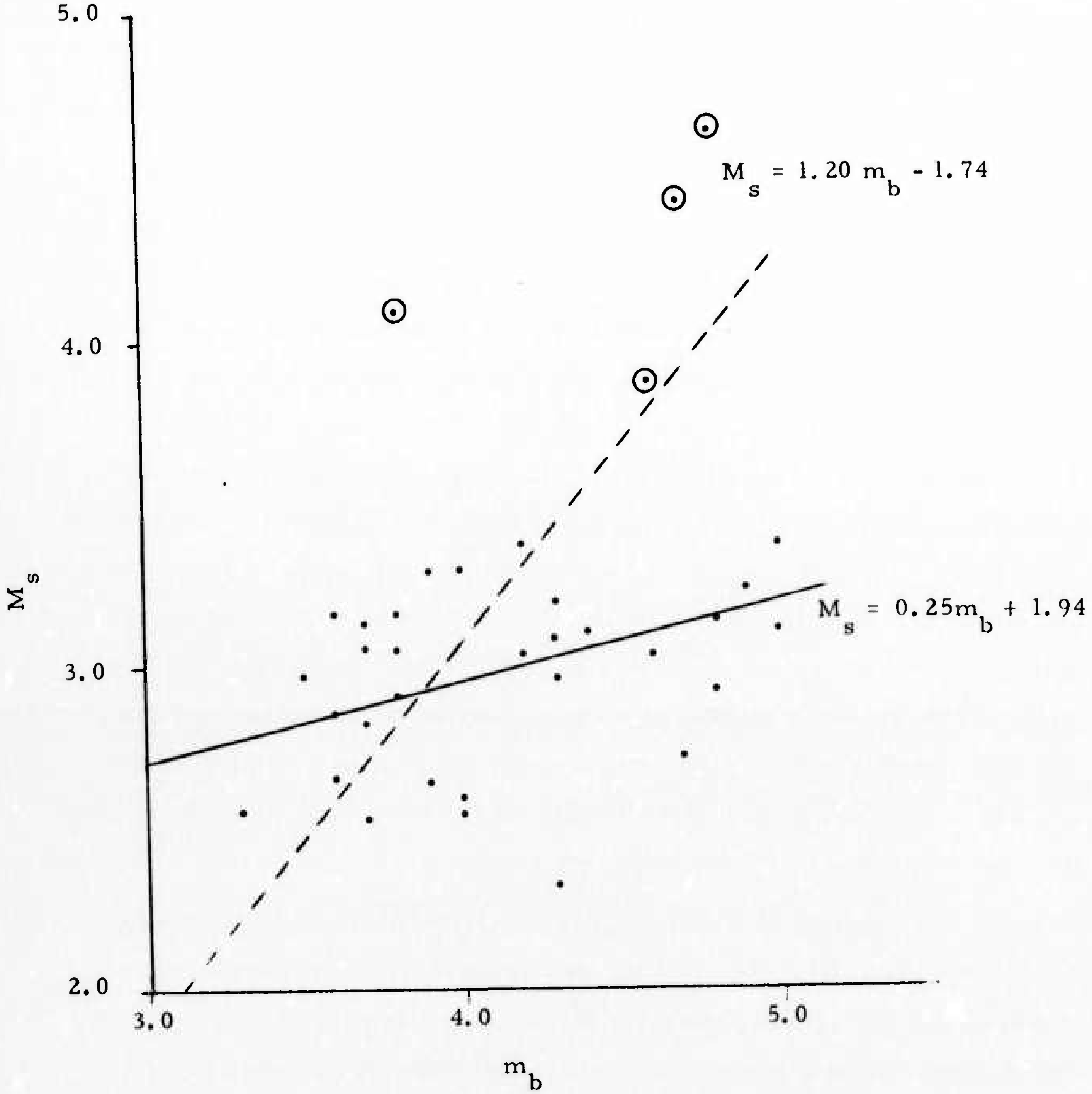



FIGURE III-6

$M_s : m_b$ PLOT OF CMF DATA - COMBINED REGION

($M_s$ derived from LR-V)

considering $M_s$ and $m_b$ to be independent of each other and determining a fit by minimizing the distances normal to a line and the data points. The method of computation is given by Lambert et al., 1973. The dashed line is a best linear fit to VLPE bandpass filtered data made over the range $4.2 \leq m_b \leq 5.5$. The equation of this line is $M_s = 1.20\, m_b - 1.74$ (Lambert et al., 1973).

The four circled points were not included in the computation of the chirp matched filter data best linear fit since they show such a large separation from the rest of the population. Investigation of the RMS noise levels for the days on which these events occurred indicate that these high $M_s$ values are due to high noise levels. For example, consider event 927 from the GTUR region. This event had an $m_b$ of 4.6 and an $M_s$ computed from chirp matched filter responses of 3.88. This $M_s$ value is an average of the values measured at stations 2 and 10. At station 2, the RMS noise value in the 20-40 second band was 4.45 $m\mu$ and the computed $M_s$ value was 3.30. At station 10, the RMS noise value in the same band was 28.37$m\mu$ and the computed $M_s$ was 4.46. Thus, it appears that these high $M_s$ values are due at least in part to high RMS noise values at some or all of the stations at which $M_s$ measurements were made.

In order for an event which was not detected on the bandpass filter response to be detected on the chirp matched filter response, the signal cannot lie far below the noise level. For example, assuming a 6 dB SNNR improvement and requiring that the matched filter produce a peak 3 dB above the noise level to call the peak a detection, the signal cannot be more than 3 dB below the noise level or no detection will occur. With this in mind, consider Figure III-6. This Figure shows that as the $m_b$ value

increases, the $M_s$ values of events detected only by a matched filter depart more and more from the bandpass filter data linear fit of $M_s = 1.20\ m_b - 1.74$. At high $m_b$ values, we are above the 50 percent bandpass filter detection level. Thus, for high $m_b$ events, the only surface waves not detected on the bandpass filter response must have abnormally low surface wave magnitudes. Detections by chirp filters of high $m_b$ events which were not detected on the bandpass filter response show that this is the case. (Figure III-6). At low $m_b$ values, we are far below the 50 percent bandpass filter detection level, and the $M_s$ values for events detected only by the chirp matched filter can be expected to be close to the $M_s$ values determined from bandpass filtered data with comparable $m_b$ values. (We note that in the case of an event detected on both bandpass and chirp matched filter, the $M_s$ value measured from the chirp response closely agrees with the $M_s$ value measured from the bandpass filter response.) Thus, $M_s$ measurements made for low $m_b$ events detected only by chirp filter may be included with bandpass data in $M_s$ - $m_b$ plots.

The variance in the data set may be ascribed to:

- Limited data
- No control of the $m_b$ parameter
- No accurate period estimate of the signal
- Station bias
- Path bias
- Source effects.

# SECTION IV

# REFERENCE WAVEFORM MATCHED FILTER EVALUATION

## A. DISCUSSION

Use of the matched filter approach implies that we know the expected waveform in order to search effectively for that waveform in a noisy record. In Section III, we considered the chirp matched filter method of obtaining the expected waveform. We now turn to the reference waveform matched filter method to obtain this expected waveform. In order to obtain a suitable expected waveform and assure that propagation effects were properly accounted for, we chose the surface waves from an event detected on the bandpass filter which had an epicenter in the area of interest.

The criteria for choosing a station-event to be a reference waveform were: good SNNR, shallow focus (less than 60 km), and location close to the majority of the other events of the region. The length of the reference waveforms was chosen in the following manner: for events at large epicentral distances, the length was selected to include multipath energy, since small changes in event epicenter location would not be expected to significantly change the multipath structure. This situation is reversed for events at small epicentral distances; for such events, small changes in event epicenter location could significantly change the multipath structure. Therefore, the lengths of reference waveforms having small epicentral distances were chosen so as to exclude any possible multipath energy.

There is always the possibility that a given reference waveform will perform poorly with most of the station-events with which it is

matched. To avoid this, two reference waveforms were chosen for each station-area whenever possible. Both reference waveforms were then matched with all appropriate station-events. The better of the two was then selected primarily on the basis of the number of detections and secondarily on the average SNNR improvement due to each. For this reason, the variation of SNNR gain due to the RWMF parameters was not determined. A list of the reference waveforms so selected is given in Table IV-1.

## B. REFERENCE WAVEFORM MATCHED FILTER RESULTS

As in the preceding section, the points to be considered in the evaluation of reference waveform matched filters are dB SNNR improvements, detection level improvements, and surface-wave magnitudes derived from the filter responses. These points will be discussed in terms of data from the two regions of interest.

### 1. dB SNNR Improvement

The dB SNNR improvement of the reference waveform matched filter over the equivalent bandpass filter was calculated by the formula given in Section II-C. SNNR improvement values were computed for every station-event detected on the bandpass filter response. The results are listed in Table IV-2 for the central Asia region and Table IV-3 for the Greece-Turkey region.

Considering those stations which detected four or more test events, the following comments on reference waveform matched filter results can be made. (The terms, "poor", "fair", "good", and "excellent" are as defined in Section III-B-1.)

TABLE IV-1

LIST OF REFERENCE WAVEFORM MATCHED FILTERS

| REGION | STATION | RWMF |
|---|---|---|
| CENA | 2 | 881 |
| CENA | 5 | 884 |
| CENA | 6 | 926 |
| CENA | 8 | 884 |
| CENA | 9 | 884 |
| CENA | 10 | 929 |
| CENA | 11 | 884 |
| GTUR | 2 | 890 |
| GTUR | 5 | 983 |
| GTUR | 6 | 890 |
| GTUR | 8 | 890 |
| GTUR | 9 | 897 |
| GTUR | 10 | 897 |
| GTUR | 11 | 890 |

TABLE IV-2

RWMF SNNR IMPROVEMENTS FOR CENTRAL ASIA
LR-V
(PAGE 1 OF 3)

APPLIED RWMF= 881- 2

| EVENT NUMBER | STATION | RWMF/TE SEP. (KM) | DB SNNR IMP OVER EQUIV. BP FILTER |
|---|---|---|---|
| 884 | 2 | 1710. | -3.2 |
| 895 | 2 | 1595. | -1.9 |
| 908 | 2 | 1078. | -1.2 |
| 909 | 2 | 1078. | 1.5 |
| 911 | 2 | 1186. | -1.0 |
| 914 | 2 | 1146. | -3.0 |
| 918 | 2 | 1871. | -1.0 |
| 926 | 2 | 1055. | 2.7 |
| 929 | 2 | 1210. | -1.1 |
| 946 | 2 | 1390. | -3.4 |
| 1091 | 2 | 592. | 0.0 |
| 1092 | 2 | 1264. | 1.1 |

MEAN SNNR IMPROVEMENT=-0.87

STANDARD DEVIATION= 1.92

APPLIED RWMF= 884- 5

| EVENT NUMBER | STATION | RWMF/TE SEP. (KM) | DB SNNR IMP OVER EQUIV. BP FILTER |
|---|---|---|---|
| 881 | 5 | 1710. | 0.3 |
| 919 | 5 | 781. | -0.1 |
| 978 | 5 | 1800. | 3.6 |

MEAN SNNR IMPROVEMENT= 1.27

## TABLE IV-2

## RWMF SNNR IMPROVEMENTS FOR CENTRAL ASIA LR-V (PAGE 2 OF 3)

APPLIED RWMF= 926- 6

| EVENT NUMBER | STATION | RWMF/TE SEP. (KM) | DB SNNR IMP OVER EQUIV. BP FILTER |
|---|---|---|---|
| 881 | 6 | 1055. | 1.8 |
| 884 | 6 | 1635. | 1.4 |
| 895 | 6 | 1476. | 3.9 |
| 908 | 6 | 11. | 0.3 |
| 911 | 6 | 1576. | 4.0 |
| 916 | 6 | 2183. | 4.0 |
| 918 | 6 | 2191. | 2.8 |
| 929 | 6 | 744. | 2.2 |
| 950 | 6 | 1259. | 1.5 |
| 952 | 6 | 934. | 2.5 |
| 954 | 6 | 1424. | 1.6 |
| 955 | 6 | 971. | -2.4 |
| 965 | 6 | 504. | -0.5 |
| 978 | 6 | 822. | 0.9 |

MEAN SNNR IMPROVEMENT= 1.71

STANDARD DEVIATION= 1.80

APPLIED RWMF= 884- 8

| EVENT NUMBER | STATION | RWMF/TE SEP. (KM) | DB SNNR IMP OVER EQUIV. BP FILTER |
|---|---|---|---|
| 881 | 8 | 1710. | -0.4 |
| 908 | 8 | 1643. | 6.1 |
| 911 | 8 | 739. | 5.9 |
| 918 | 8 | 781. | 2.9 |
| 929 | 8 | 901. | 5.3 |
| 946 | 8 | 1917. | 1.3 |
| 950 | 8 | 2662. | 4.6 |
| 965 | 8 | 1273. | -0.5 |

MEAN SNNR IMPROVEMENT= 3.15

STANDARD DEVIATION= 2.74

## TABLE IV-2

## RWMF SNNR IMPROVEMENTS FOR CENTRAL ASIA
## LR-V
## (PAGE 3 OF 3)

APPLIED RWMF= 884- 9

| EVENT NUMBER | STATION | RWMF/TE SEP. (KM) | DB SNNR IMP OVER EQUIV. BP FILTER |
|---|---|---|---|
| 908 | 9 | 1643. | 5.5 |
| 911 | 9 | 739. | 9.9 |
| 916 | 9 | 778. | 4.6 |
| 918 | 9 | 782. | 4.6 |
| 950 | 9 | 2662. | 0.9 |
| 954 | 9 | 266. | 6.4 |
| 965 | 9 | 1273. | 3.7 |
| 978 | 9 | 1840. | 2.7 |

MEAN SNNR IMPROVEMENT= 4.79

STANDARD DEVIATION= 2.67

APPLIED RWMF= 929-10

| EVENT NUMBER | STATION | RWMF/TE SEP. (KM) | DB SNNR IMP OVER EQUIV. BP FILTER |
|---|---|---|---|
| 918 | 10 | 1539. | 0.5 |

APPLIED RWMF= 884-11

| EVENT NUMBER | STATION | RWMF/TE SEP. (KM) | DB SNNR IMP OVER EQUIV. BP FILTER |
|---|---|---|---|
| 881 | 11 | 1710. | -1.4 |
| 914 | 11 | 2492. | -1.4 |
| 918 | 11 | 781. | -4.2 |
| 926 | 11 | 1635. | 2.2 |
| 929 | 11 | 901. | 1.1 |
| 946 | 11 | 1917. | -2.4 |
| 961 | 11 | 2309. | -1.7 |
| 965 | 11 | 1273. | 0.5 |
| 1044 | 11 | 365. | -1.8 |
| 1069 | 11 | 2447. | -1.3 |

MEAN SNNR IMPROVEMENT=-1.04

STANDARD DEVIATION= 1.84

## TABLE IV-3

## RWMF SNNR IMPROVEMENTS FOR GREECE-TURKEY REGION
## LR-V
## (PAGE 1 OF 2)

APPLIED RWMF= 983- 5

| EVENT NUMBER | STATION | RWMF/TE SEP. (KM) | BP SNNR IMP OVER EQUIV. BP FILTER |
|---|---|---|---|
| 890 | 5 | 794. | 1.0 |
| 933 | 5 | 977. | 2.4 |
| 971 | 5 | 997. | -1.1 |
| 1081 | 5 | 156. | 4.3 |

MEAN SNNR IMPROVEMENT= 1.65

STANDARD DEVIATION= 2.28

APPLIED RWMF= 890- 6

| EVENT NUMBER | STATION | RWMF/TE SEP. (KM) | BP SNNR IMP OVER EQUIV. BP FILTER |
|---|---|---|---|
| 897 | 6 | 227. | 4.0 |
| 927 | 6 | 343. | 1.7 |
| 933 | 6 | 284. | 4.2 |
| 941 | 6 | 315. | 1.2 |
| 956 | 6 | 1165. | 2.6 |
| 957 | 6 | 239. | 0.3 |
| 968 | 6 | 260. | 4.0 |
| 972 | 6 | 750. | 4.5 |
| 983 | 6 | 794. | 0.7 |
| 1052 | 6 | 674. | 0.9 |

MEAN SNNR IMPROVEMENT= 2.41

STANDARD DEVIATION= 1.64

TABLE IV-3

RWMF SNNR IMPROVEMENTS FOR GREECE-TURKEY REGION
LR-V
(PAGE 2 OF 2)

APPLIED RWMF= 890- 8

| EVENT NUMBER | STATION | RWMF/TE SEP. (KM) | DB SNNR IMP OVER EQUIV. BP FILTER |
|---|---|---|---|
| 897 | 8 | 227. | 6.4 |
| 956 | 8 | 1165. | 5.1 |

MEAN SNNR IMPROVEMENT= 5.75

APPLIED RWMF= 897- 9

| EVENT NUMBER | STATION | RWMF/TE SEP. (KM) | DB SNNR IMP OVER EQUIV. BP FILTER |
|---|---|---|---|
| 890 | 9 | 227. | 3.5 |
| 956 | 9 | 1119. | 7.3 |
| 983 | 9 | 759. | 0.9 |

MEAN SNNR IMPROVEMENT= 3.90

- Station 2 - SNNR improvements were poor for events from central Asia
- Station 5 - SNNR improvements were fair for events from Greece-Turkey
- Station 6 - SNNR improvements were fair for events from central Asia, and good for events from Greece-Turkey
- Station 9 - SNNR improvements were excellent for events from central Asia
- Station 11 - SNNR improvements were poor for events from central Asia.

The overall average SNNR improvement was 1.3 dB for central Asia, and 3.1 dB for Greece-Turkey. A larger data base for Greece-Turkey will be necessary to allow comparison of individual stations between these regions and central Asia.

As in the case of chirp matched filters, the standard deviations associated with the mean values of SNNR improvements were large. The possibility of the high and low values being geographically separated will need to be investigated in the future.

The effect of reference waveform-test event separation upon SNNR improvement is illustrated by Figure IV-1. (Only the CENA data were plotted, since there were too few GTUR data points available to make a meaningful plot.) A straight-line least-mean-square-error fit to the data points is shown.

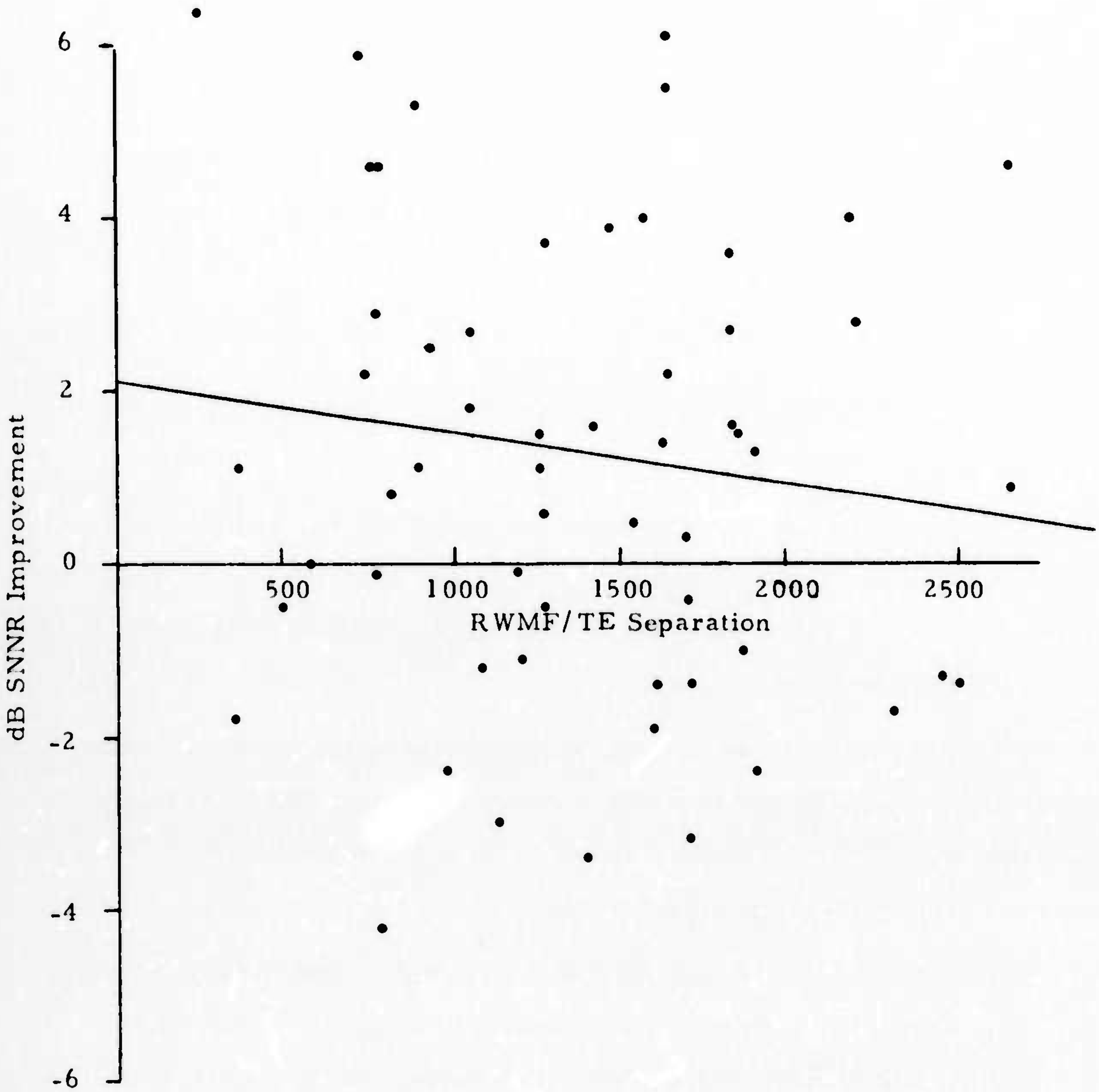



FIGURE IV-1

RWMF - TEST EVENT SEPARATION VERSUS dB SNNR IMPROVEMENT
CENA
(LR-V COMPONENT)

Although there is an extremely large variation in the data, the plot seems to indicate that the SNNR improvement obtained by the reference waveform matched filters decreases gradually with increasing reference waveform-test event separation. The slope of the fitted line is -0.6 dB/1000 km, as compared to a slope of -3.0 dB/1000 km for ALPA data.

2. Surface-Wave Detection Using Reference Waveform Matched Filters

Using the detection criteria given in Section II-C, the detection capability of reference woveform matched filters was evaluated for the central Asia region, the Greece-Turkey region, and the combined central Asia-Greece-Turkey region. This evaluation was performed in terms of seismic events and the VLPE network. The results are as follows:

- CENA - Fifteen events were detected on the bandpass filter response. An additional 20 events were detected on the reference waveform matched filter response, resulting in a 133 percent increase in the number of events detected.
- GTUR - Five events were detected on the bandpass filter response. An additional 8 events were detected on the reference waveform matched filter response, resulting in a 160 percent increase in the number of events detected.
- Combined CENA and GTUR - Twenty events were detected on the bandpass filter response. An additional 28 events were resulting in a 140 percent increase in the number of events detected.

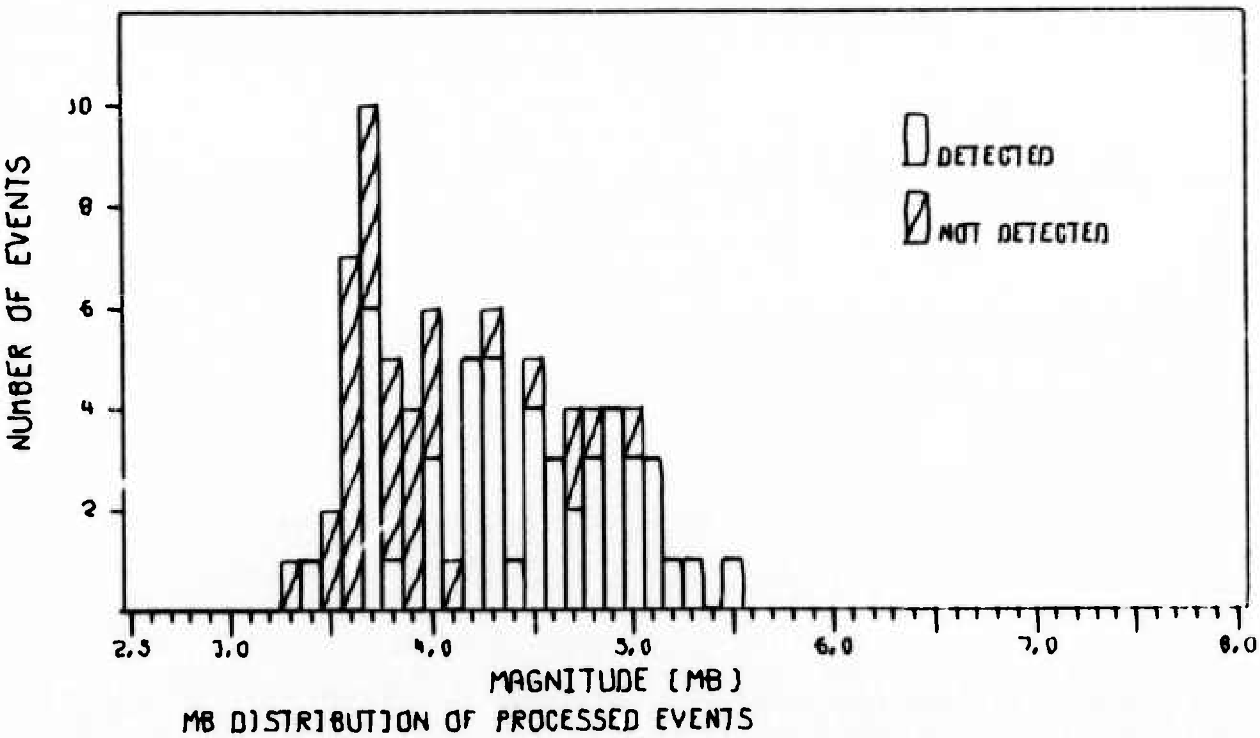
Although the percentage increase in the number of events detected differs for the two individual regions, we note that overall the number of detections is more than doubled by the use of reference waveform matched filters.

The detection capability of reference waveform matched filters in a network sense is illustrated by Figure IV-2, which shows the bodywave magnitude distribution and maximum-likelihood detectability curve for the combined central Asia and Greece-Turkey region events. Comparing this figure with the corresponding bandpass filter maximum-likelihood detectability curve of Figure II-2, we find that the use of reference waveform matched filters lowered the 50 percent detection level from 4.72 to 4.01 $m_b$ units and the 90 percent detection level from 5.25 to 4.91 $m_b$ units.

3. Surface-Wave Magnitudes from Reference Waveform Matched Filter Data

Surface-wave magnitudes were computed from reference waveform matched filter data using the method described in Section II-B-3 for those station-events detected on the matched filter response but not on the bandpass filter response. When SNNR improvement values were available for four or more events recorded at a station, the average of those values was used in the surface-wave magnitude calculation. When less than four values were available, the overall average SNNR improvement was used.

From Tables IV-2 and IV-3, the SNNR improvements used were:



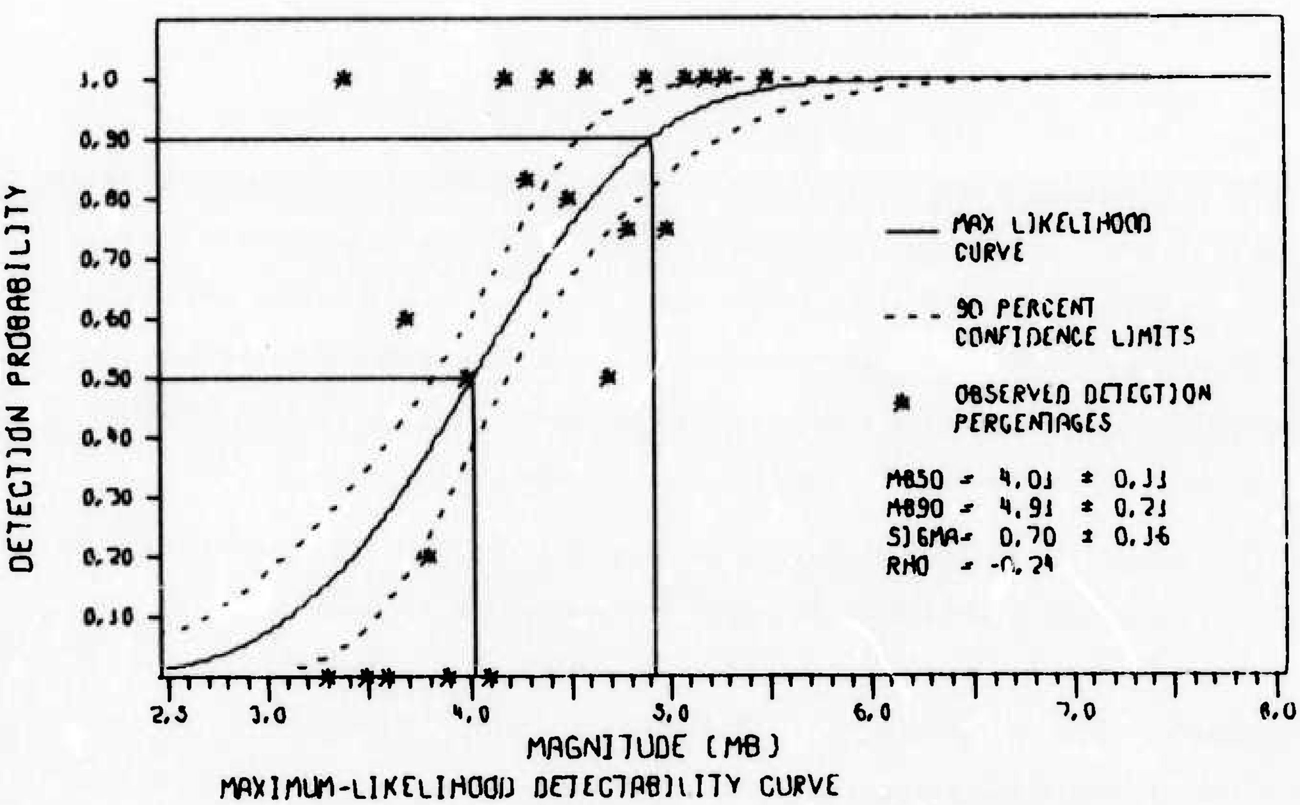




FIGURE IV-2

DETECTION STATISTICS FOR THE COMBINED REGION-RWMF DETECTIONS

| Station | SNNR Improvements | |
|---|---|---|
| | CENA | GTUR |
| 2 | -0.9 | 2.8* |
| 5 | 1.3* | 1.6 |
| 6 | 1.7 | 2.4 |
| 8 | 3.2 | 2.8* |
| 9 | 4.8 | 2.8* |
| 10 | 1.3* | 2.8* |
| 11 | -1.0 | 2.8* |

where all values are in dB. An asterisk denotes the use of the overall average SNNR improvement value.

The surface-wave magnitude values calculated using the above SNNR improvement values are shown in Figure IV-3. When $M_s$ values were computed at two or more stations for a given event, they were averaged to reduce the variance. The resulting plot shows network average $M_s$ values with one or more stations reporting. The $M_s$ values are for events detected by reference waveform matched filters but not by the bandpass filtered data as described in Section III-B-3. The solid line is a best linear fit to the data, computed by considering $M_s$ and $m_b$ to be independent of each other and determining a fit by minimizing the distances normal to a line and the data points. The circled points were not included in the computation of this linear fit, since three show anomalously high values and one an anomalously low value. As in the case of the chirp matched filter data, it is believed that the high values are due at least in part to high RMS noise values. The anomalously low $M_s$ value may be a false alarm.

The data of Figure IV-3 present the same picture as did the chirp matched filter data. At low $m_b$ values, the $M_s$ values computed for events detected only by the reference waveform matched filters are comparable to the $M_s$ values for bandpass filtered data. At higher $m_b$ values (near or above the 50 percent detection level), the $M_s$ values computed for events detected only by the reference waveform matched filters are much lower than the $M_s$ values determined from bandpass filtered data.

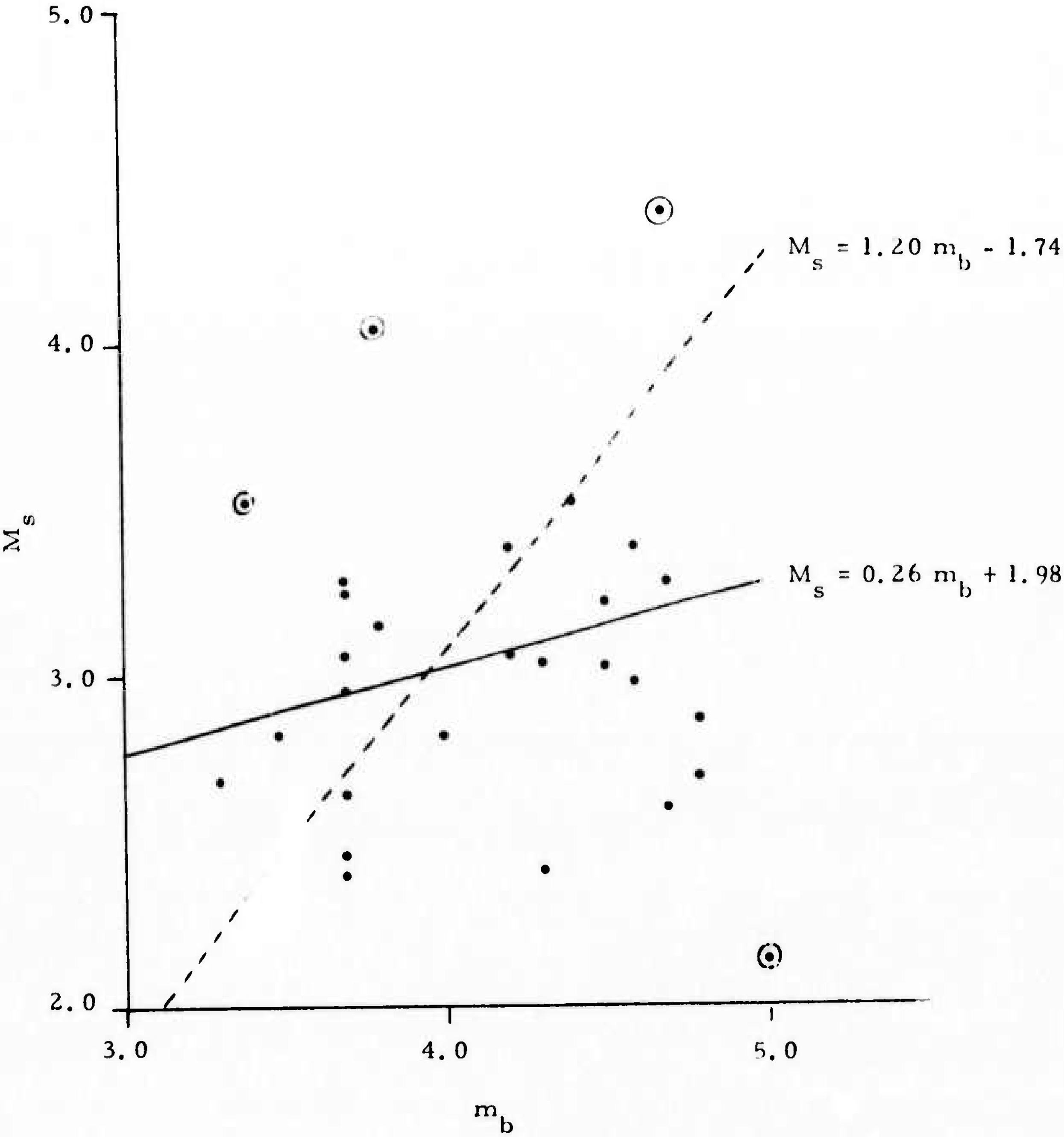



FIGURE IV-3

$M_s$ :: $m_b$ PLOT OF RWMF DATA - COMBINED REGION

($M_s$ Derived from LR-V)

# SECTION V

# THREE-COMPONENT ADAPTIVE PROCESSOR EVALUATION

It has been previously reported (Lane, 1973) that the three-component adaptive processor can yield as much as 8 dB improvement in the signal-plus-noise to noise ratio when applied to single site data. However, due to unmatched instrumental phase responses between the horizontal and vertical components of the VLPE stations, it is not expected that such SNNR improvements will be realized when this method is applied to VLPE data. In the following, we assess the value of the three-component adaptive processor when applied to VLPE data in its present form to determine whether this method can be used in spite of this problem.

## A. DISCUSSION

The three-component adaptive filter (TCA) is designed to improve the detectability of long-period Love and Rayleigh waves by utilizing the known phase relationships between these surface waves. (Lane 1973). The process examines three mutually perpendicular seismometer traces and after dividing the data into overlapping segments designs a new filter for each segment (i.e., it is adaptive).

When considering Rayleigh waves, the TCA examines only the radial and vertical components. Ideally, fundamental Rayleigh wave signals are $90^{\circ}$ out of phase on these components, and consequently, the filter is designed to emphasize this apparent polarization of particle motion.

Consider the k-th segment of data, and let $V^*_k(\nu)$ and $R^*_k(\nu)$ be the Fourier transforms at the $\nu$-th frequency of the vertical and radial traces, respectively. As complex functions, these components may be expressed as:

$$V^*_k(\nu) = \left| V^*_k(\nu) \right| e^{i\theta_k(\nu)}$$

$$R^*_k(\nu) = \left| R^*_k(\nu) \right| e^{i\varphi_k(\nu)}$$

where $i = \sqrt{-1}$ and $\theta_k(\nu), \varphi_k(\nu)$ are the phase spectra of the vertical and radial traces, respectively. Then, the relative phase angle $\psi_k(\nu)$ is given by:

$$\psi_k(\nu) = \theta_k(\nu) - \varphi_k(\nu),$$

and the filter transfer function (filter weight function) is defined by:

$$F_k(\nu) = \sin^N(\psi_k(\nu)),$$

where N must be an even integer in order to guarantee that $F_k(\nu)$ is non-negative. This exponent determines the degree of rejection by the filter for frequencies whose relative phase angles are undesirable. Since Rayleigh wave signals are usually contaminated by noise (and, occasionally by higher modes), the relative phase angle will never be exactly $90^\circ$, and subsequently, care must be taken to not use too large an exponent or else significant amounts of signal energy will be rejected. For the data processed herein, a value of $N = 6$ was selected with segments chosen to be 64 points (128 seconds) in length. These values were suggested by Lane, (1973). Other values are currently being examined to determine whether or not these are the optimum values.

The bandpassed Fourier transforms of the traces are then multiplied by this filter to give the transforms $\overline{V}_k(\nu)$, $\overline{R}_k(\nu)$ of the filtered segments:

$$\bar{V}_k(\nu) = V^*_k(\nu) \bullet F_k(\nu)$$

$$\bar{R}_k(\nu) = R^*_k(\nu) \bullet F_k(\nu).$$

These traces are then inverse transformed back to the time domain. Next, the k + 1 segment of time domain data is examined and defined to begin at the mid-point of the k-th segment. After filtering as above, a weighted average of the resultant k and k + 1 segments is formed over their common interval. In particular, at the i-th time point the final value is given by:

$$V^f_k(t_i) = V_{k+1}(t_i)\left(\frac{d_i}{\ell}\right) + V_k(t_i)\left(1 - \frac{d_i}{\ell}\right),$$

where

$\ell$ = length of overlapping segment,

$d_i$ = distance from beginning of k + 1 segment to $t_i$-th point.

When considering Love waves, the TCA analyses the transverse and radial components and enhances those signal elements which are on azimuth. In particular, the azimuthal filter is defined (similarly to the polarization filter) by: $F_k(\nu) = \cos^N(\xi_k(\nu))$, where N is an even integer, $\nu$ is the frequency and $\xi_k(\nu)$ is the difference between the expected azimuth of arrival of the suspected event, $\alpha$, and the apparent azimuth of arrival as determined by the transverse and radial traces for the k-th segment. In particular,

$$\xi_k(\nu) = \alpha - \tan^{-1}\left\{\frac{|R^*_k(\nu)|}{|T^*_k(\nu)|}\right\},$$

where $R^*_k(\nu)$ and $T^*_k(\nu)$ are the Fourier transforms at the $\nu$-th frequency for the k-th segment of the radial and the transverse traces, respectively.

The transverse and radial time domain traces are then treated analogously to the Rayleigh wave process presented above but with the transverse component being considered rather than the vertical component and with the filter transfer function redesigned as above.

The data base used to evaluate the TCA technique was essentially the same as that used to evaluate the matched filter techniques. However, if one component of a station-event contained malfunctions, it could not be processed by the TCA, but could be processed by matched filters. Therefore, the data base for the TCA evaluation is somewhat smaller than that used for the matched filter evaluation. From the Tables of the Appendix A, we see that 204 station-events from central Asia and 97 station-events from Greece-Turkey were available for processing by the TCA technique.

## B. THREE-COMPONENT ADAPTIVE PROCESSOR RESULTS

As in the preceding sections, the points to be considered in the evaluation of the TCA technique are dB SNNR improvements, detection level improvements, and surface-wave magnitudes derived from the TCA responses. These points will be discussed in terms of data from the two regions of interest.

### 1. dB SNNR Improvement

The dB SNNR improvement of the TCA processor over the equivalent bandpass filter was calculated by the formula given in Section II-C. The RMS noise values were determined from noise gates immediately preceding the signal gates. The results are listed in Table V-1 for central Asia and Table V-2 for Greece-Turkey.

Considering those stations which detected four or more test events, the following comments on the three-component adaptive processor results can be made. (The terms "poor", "fair", "good", and "excellent" are defined in Section III-B-1.)

TABLE V-1

TCA SNNR IMPROVEMENTS FOR THE CENTRAL ASIA REGION
(PAGE 1 OF 3)

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 881 | 2 | -3.8 |
| 884 | 2 | 0.7 |
| 895 | 2 | -2.0 |
| 908 | 2 | 2.1 |
| 909 | 2 | 3.3 |
| 911 | 2 | 2.6 |
| 914 | 2 | 3.8 |
| 918 | 2 | 3.3 |
| 926 | 2 | 0.2 |
| 929 | 2 | 1.8 |
| 946 | 2 | 6.7 |
| 1092 | 2 | 0.8 |

MEAN SNNR IMPROVEMENT= 1.62

STANDARD DEVIATION= 2.75

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 881 | 5 | 2.2 |
| 884 | 5 | 1.0 |
| 978 | 5 | 2.9 |

MEAN SNNR IMPROVEMENT= 2.03

TABLE V-1

TCA SNNR IMPROVEMENTS FOR THE CENTRAL ASIA REGION
(PAGE 2 OF 3)

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 881 | 6 | 0.2 |
| 884 | 6 | 4.0 |
| 895 | 6 | 0.6 |
| 911 | 6 | 0.6 |
| 916 | 6 | -1.0 |
| 918 | 6 | -0.1 |
| 929 | 6 | 1.1 |
| 950 | 6 | 2.5 |
| 952 | 6 | 1.7 |
| 954 | 6 | 1.2 |
| 965 | 6 | -3.8 |
| 978 | 6 | 0.6 |

MEAN SNNR IMPROVEMENT= 0.63

STANDARD DEVIATION= 1.9[illegible]

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 881 | 8 | -0.5 |
| 884 | 8 | 1.4 |
| 908 | 8 | 1.6 |
| 911 | 8 | 2.8 |
| 918 | 8 | 4.0 |
| 929 | 8 | 2.1 |
| 950 | 8 | 0.6 |
| 965 | 8 | 0.7 |

MEAN SNNR IMPROVEMENT= 1.59

STANDARD DEVIATION= 1.40

TABLE V-1

TCA SNNR IMPROVEMENTS FOR THE CENTRAL ASIA REGION
(PAGE 3 OF 3)

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 884 | 9 | 1.4 |
| 908 | 9 | 2.3 |
| 911 | 9 | 2.0 |
| 916 | 9 | 4.2 |
| 918 | 9 | -2.9 |
| 950 | 9 | -0.1 |
| 954 | 9 | -0.3 |
| 965 | 9 | 4.1 |
| 978 | 9 | 2.9 |

MEAN SNNR IMPROVEMENT= 1.51

STANDARD DEVIATION= 2.29

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 918 | 10 | 1.4 |
| 929 | 10 | -0.6 |

MEAN SNNR IMPROVEMENT= 0.40

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 881 | 11 | 5.5 |
| 884 | 11 | 2.6 |
| 918 | 11 | -4.0 |
| 929 | 11 | 6.9 |
| 946 | 11 | 2.7 |
| 961 | 11 | 3.9 |
| 965 | 11 | 2.2 |
| 1044 | 11 | 6.0 |
| 1069 | 11 | 0.7 |

MEAN SNNR IMPROVEMENT= 2.94

STANDARD DEVIATION= 3.29

## TABLE V-2

## TCA SNNR IMPROVEMENTS FOR THE GREECE-TURKEY REGION (PAGE 1 OF 2)

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 890 | 2 | 1.1 |

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 890 | 5 | -5.0 |
| 971 | 5 | 2.0 |
| 983 | 5 | -2.2 |
| 1081 | 5 | 1.2 |

MEAN SNNR IMPROVEMENT=-1.00

STANDARD DEVIATION= 3.23

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 890 | 6 | -0.3 |
| 897 | 6 | 2.8 |
| 912 | 6 | 0.7 |
| 927 | 6 | -1.8 |
| 933 | 6 | 3.3 |
| 941 | 6 | 1.4 |
| 956 | 6 | 1.7 |
| 957 | 6 | 0.1 |
| 968 | 6 | 4.2 |
| 972 | 6 | 0.3 |
| 983 | 6 | -1.5 |
| 1028 | 6 | 1.1 |
| 1052 | 6 | 0.6 |

MEAN SNNR IMPROVEMENT= 0.97

STANDARD DEVIATION= 1.75

TABLE V-2

TCA SNNR IMPROVEMENTS FOR THE GREECE-TURKEY REGION
(PAGE 2 OF 2)

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 890 | 8 | -1.5 |
| 897 | 8 | -0.7 |
| 956 | 8 | 0.2 |

MEAN SNNR IMPROVEMENT=-0.67

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 890 | 9 | 2.0 |
| 897 | 9 | 0.1 |
| 956 | 9 | -0.9 |
| 983 | 9 | 2.4 |

MEAN SNNR IMPROVEMENT= 0.90

STANDARD DEVIATION= 1.56

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 897 | 10 | 3.5 |

| EVENT NUMBER | STATION | DB SNNR IMP. OVER EQUIVALENT BP FILTER |
|---|---|---|
| 890 | 11 | 1.4 |

- Station 2 - SNNR improvements were fair for events from CENA
- Station 6 - SNNR improvements were poor for events from CENA and GTUR
- Station 8 - SNNR improvements were fair for events from CENA
- Station 9 - SNNR improvements were fair for events from CENA and poor for events from GTUR
- Station 11 - SNNR improvements were good for events from CENA.

The overall average SNNR improvement was 1.6 dB for central Asia and 0.6 dB for Greece-Turkey. Although a larger data base for Greece-Turkey would be necessary to allow comparison of more individual stations, it is immediately obvious that only low mean values of SNNR improvement were obtained from this technique. These low values of SNNR improvement are primarily due to unmatched instrumental phase responses between the horizontal and vertical components. Lambert (Lambert et al., 1973) recognized this problem and discussed it in terms of the errors in analytic rotation of the north and east components to transverse and radial components. Visual observation of bandpass filtered data shows that, in general, the vertical and horizontal Rayleigh waves are not $90^{o}$ out of phase.

2. Surface Wave Detection Using the Three-Component Adaptive Processor

Using the detection criteria of Section II-C, the detection capability of the three-component adaptive processor was evaluated for the central Asia region, the Greece-Turkey region, and the combined central Asia and Greece-Turkey regions. This evaluation was performed in terms of seismic events and the VLPE network. The results are as follows:

- CENA - Fifteen events were detected on the bandpass filter response. An additional two events were detected on the three-component adaptive processor response, resulting in a 13 percent increase in the number of events detected.

- GTUR - Five events were detected on the bandpass filter response. No additional events were detected on the three-component adaptive processor response.

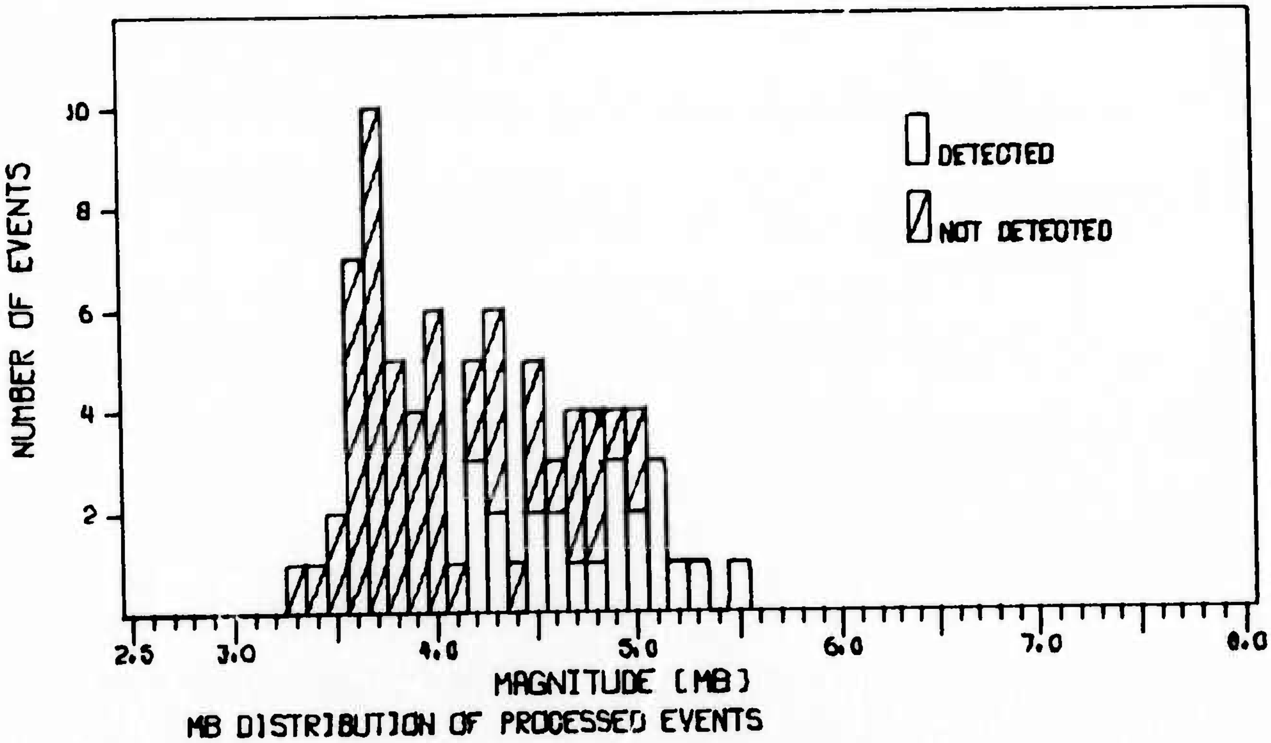
- Combined CENA and GTUR - Twenty events were detected on the bandpass filter response. An additional two events were detected on the three-component adaptive processor response, resulting in a 10 percent increase in the number of events detected.

Thus, we see that the three-component adaptive processor, as currently used, does not make any significant changes in the number of events detected.

The detection capability of the three-component adaptive processor is illustrated by Figure V-1. This figure shows the bodywave magnitude distribution and maximum-likelihood detectability curves for the combined central Asia and Greece-Turkey region events. Comparing this figure with the corresponding bandpass filter maximum-likelihood detectability curve of Figure II-2, we find that the 50 and 90 percent detection levels are virtually unchanged.

### 3. $M_s$ Computations for TCA

Within the TCA program an $M_s$ value for the vertical component was computed for the maximum peak-to-peak amplitude within a signal gate. When the event was considered to be detected, this was its assigned (initial) $M_s$ value, designated $M'_s$. The following program formula was employed:



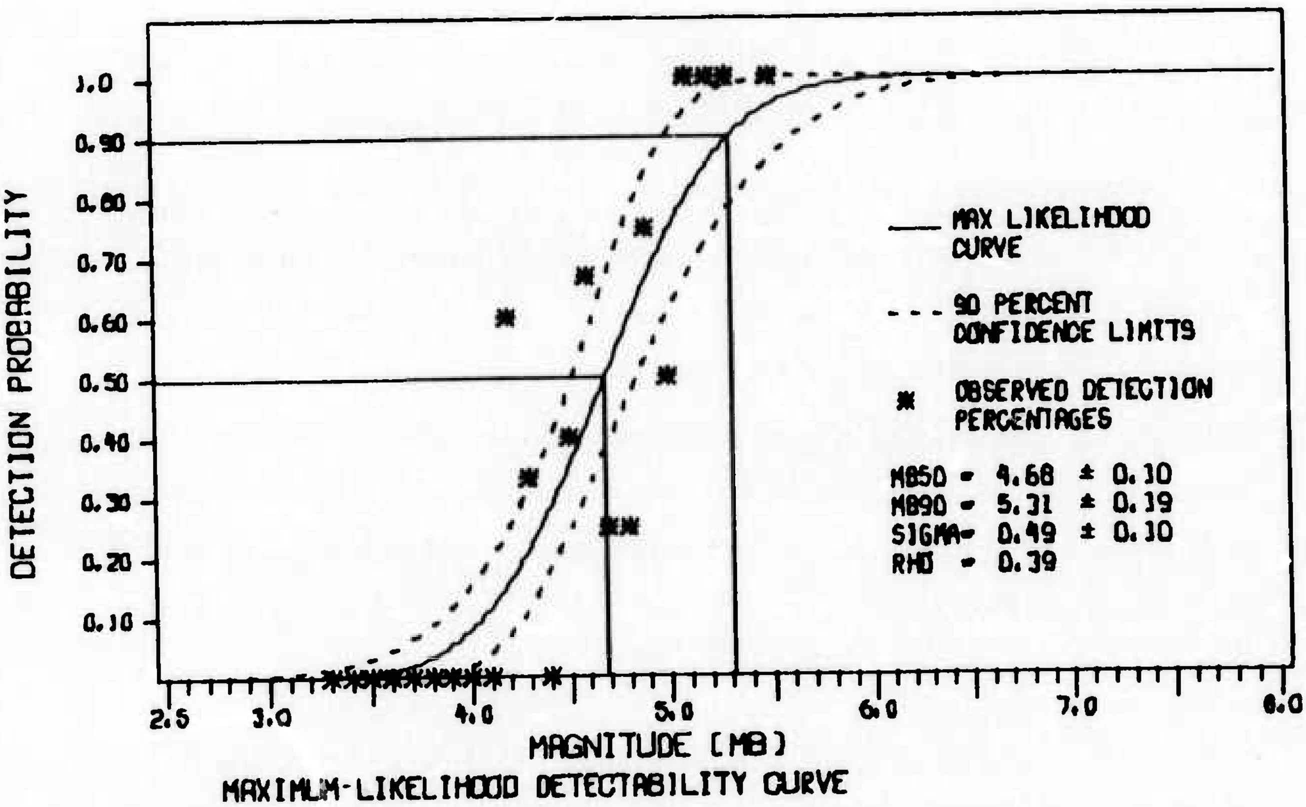




FIGURE V-1

DETECTION STATISTICS FOR THE COMBINED REGION - TCA DETECTIONS

$$M_s' = \log_{10} \left( \frac{A}{T * V_k^f (t_i)} \right) + \log \Delta^o + 1.12$$

where:

| | | |
|---|---|---|
| $A$ | = | Maximum peak-to-peak amplitude ($m\mu$) |
| $T$ | = | Period corresponding to A |
| $\Delta^o$ | = | Epicentral distance from event to station (degrees) |
| $V_k^f (t_i)$ | = | Final filter weight utilized at the $t_i$ -th time point where the $t_i$-th point was the mid-zero crossing of the measured peak-to-peak wave. |

This formula was subsequently corrected for the station's instrument response to arrive at a final $M_s$ value, $M_s$ (TCA):

$$M_s (TCA) = M_s' - \log_{10} (G (T))$$

where G (T) = station's instrument response at period T.

In an effort to assure that reasonable $M_s$ values were being generated by the program we examined certain February 1973 events. These events were selected to fulfill the following requirements:

- The events were detected by the bandpass filter on both vertical and transverse components (at each station considered.)
- All three components were functioning. (This insured that vertical and transverse TCA output would be meaningful).
- At least two stations detected the event and these stations were on approximately the same epicenter-to-station azimuth. This requirement minimized event $M_s$ (bandpass) variations resulting from path effects.

There were six station-events which satisfied all of the above requirements. For these events the $M_s$ (bandpass) and the $M_s$ (TCA) were found to be comparable. The results are presented in Table V-3. Thus, we concluded that the $M_s$ (TCA) values produced by the program were reasonable.

As shown in Figure V-2, the poor detection capability of the three-component adaptive processor resulted in only 12 $M_s$ values of events detected on the three-component adaptive processor but not the bandpass filter. For comparison, the linear fit to VLPE bandpass filtered data (Lambert et al., 1973) is presented. Since there are only 12 $M_s$ values available in a narrow $m_b$ range, a linear fit was not computed for these values. There is no trend observable in these data points comparable to that of the matched filter data of Figure III-6 and IV-3. It is not known whether this is due to errors in the computation of $M_s$ from three-component adaptive processor data or is merely due to the limited number of data points.

TABLE V-3

$M_s$ (TCA) VERSUS $M_s$ (BANDPASS)

| Event | $m_b$ | Station | $M_s$ (TCA) | $M_s$ (Bandpass) | $\Delta^o$ | Azimuth |
|---|---|---|---|---|---|---|
| 956 | 4.5 | 6 | 3.99 | 3.98 | $25^o$ | 340 |
| | | 9 | 4.32 | 4.20 | $97^o$ | 322 |
| 965 | 4.8 | 8 | 4.05 | 4.04 | $96^o$ | 56 |
| | | 11 | 3.40 | 3.25 | $41^o$ | 77 |
| 983 | 4.2 | 6 | 3.95 | 3.82 | $24^o$ | 340 |
| | | 9 | 3.57 | 3.67 | $96^o$ | 322 |

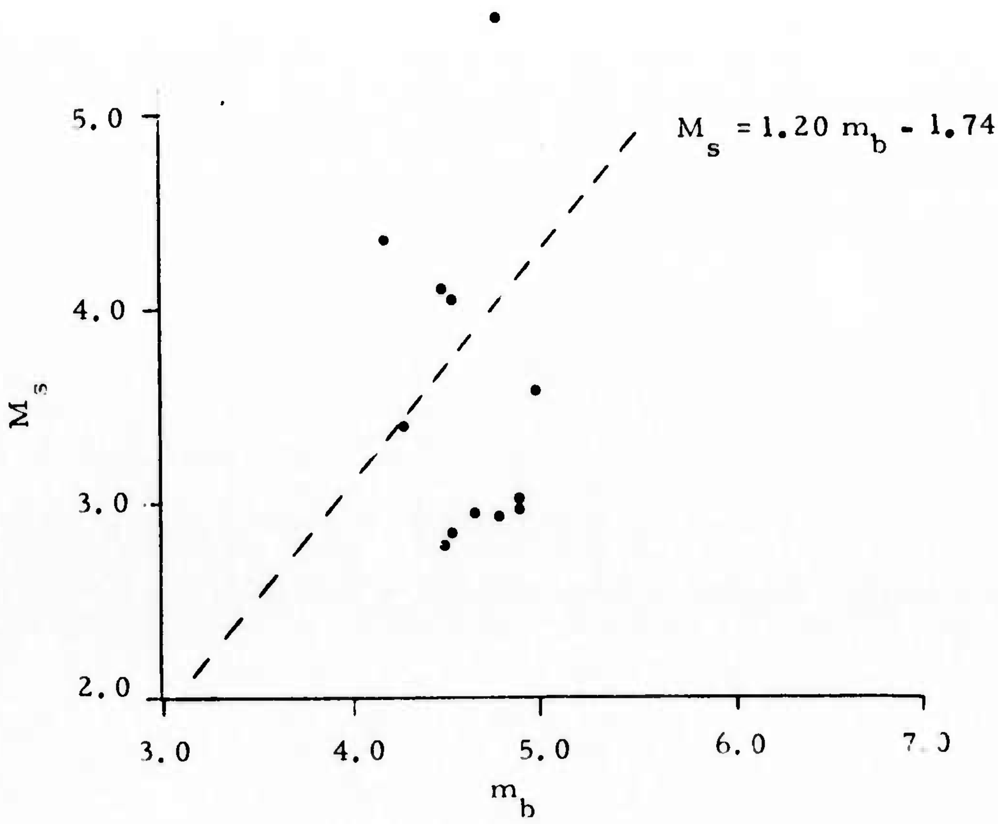



FIGURE V-2

$M_s$ : $m_b$ PLOT OF TCA DATA

(Combined Region)

## SECTION VI

## DISCUSSION AND SUMMARY

### A. COMPARISON OF THE TECHNIQUES

Each of the three data enhancement techniques has now been evaluated in terms of dB SNNR improvement, detection level improvement, and surface-wave magnitudes. We now compare these techniques in an attempt to determine which, if any, is superior to the others for a given region.

#### 1. Comparison of SNNR Improvements

The mean SNNR improvements and associated standard deviations for each technique are listed by region in Table VI-1. In each region, the best technique is judged to be that one which displays the largest mean SNNR improvement with the smallest associated deviation. Using this criterion, the best technique for data enhancement, by region is:

CENA - The chirp matched filter technique outperformed the other two.

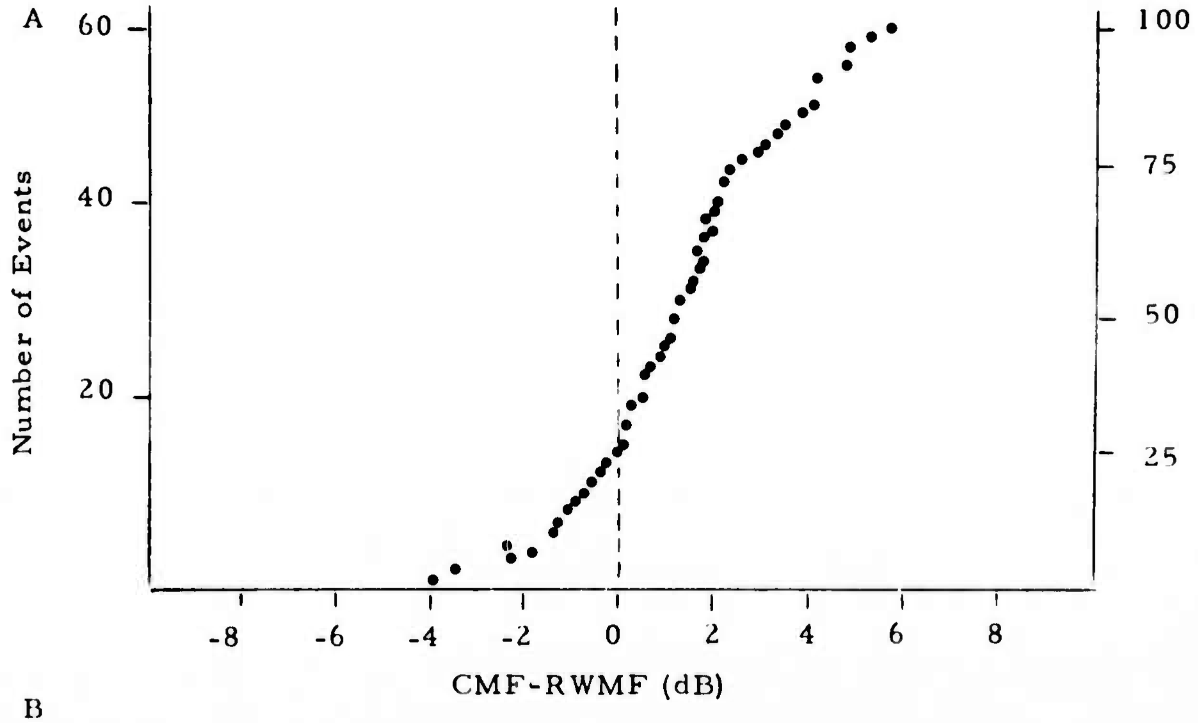
GTUR - The chirp matched filter technique outperformed the other two. However, the reference waveform matched filter technique was almost as good.

Another comparison of the three techniques is given by Figures VI-1 and VI-2. Figure VI-1 indicates that approximately 75 percent of the Central Asia test events showed higher chirp SNNR improvements than reference waveform SNNR improvements, and approximately 67 percent

TABLE VI-1

COMPARISON OF CMF, RWMF, AND TCA SNNR IMPROVEMENTS

| Region | Technique | Mean | Standard Deviation |
|---|---|---|---|
| CENA | CMF | 2.6 | 2.2 |
| | RWMF | 1.3 | 2.9 |
| | TCA | 1.6 | 2.3 |
| GTUR | CMF | 3.4 | 2.0 |
| | RWMF | 2.8 | 2.2 |
| | TCA | 0.6 | 1.9 |



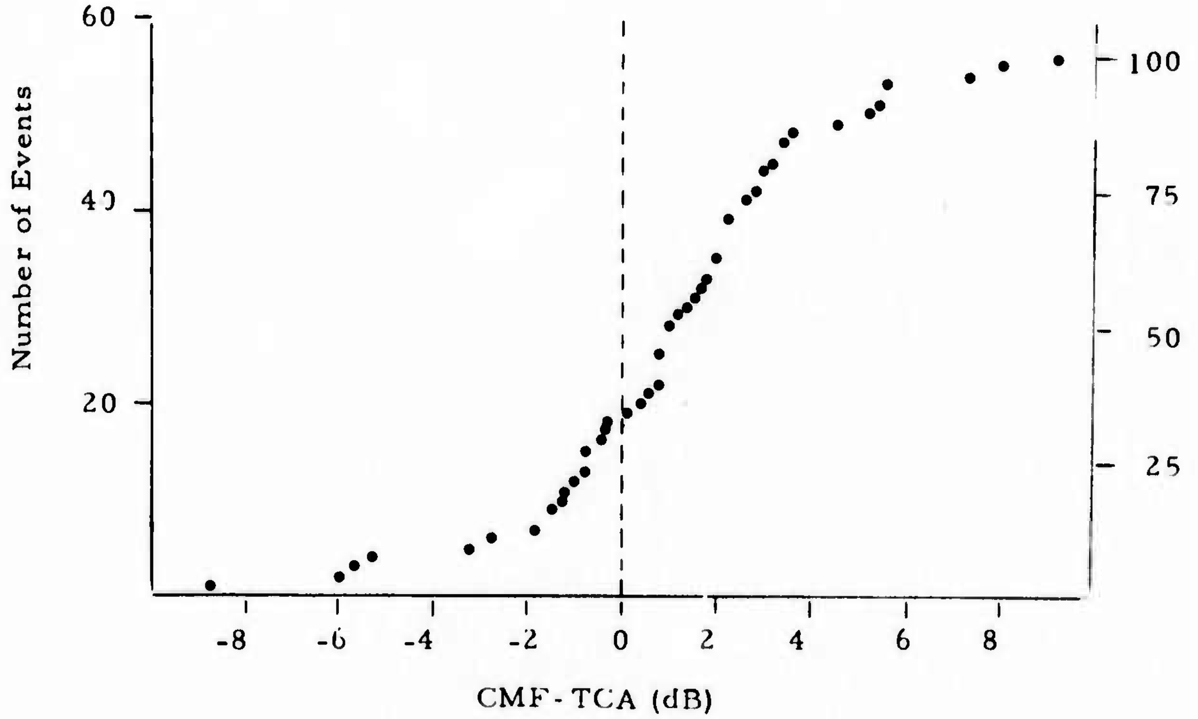
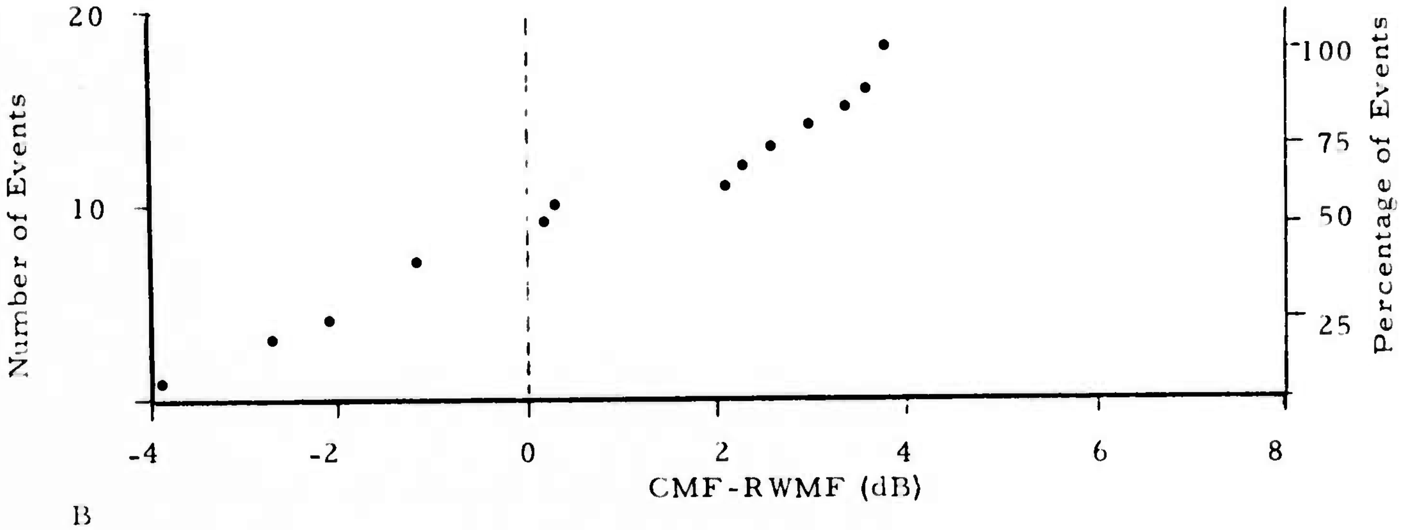




FIGURE VI-1

CUMULATIVE DISTRIBUTION OF CMF-RWMF SNNR IMP (A) AND CMF-TCA SNNR IMP (B) FOR CENA TEST EVENTS (VERTICAL COMPONENT)

A




B

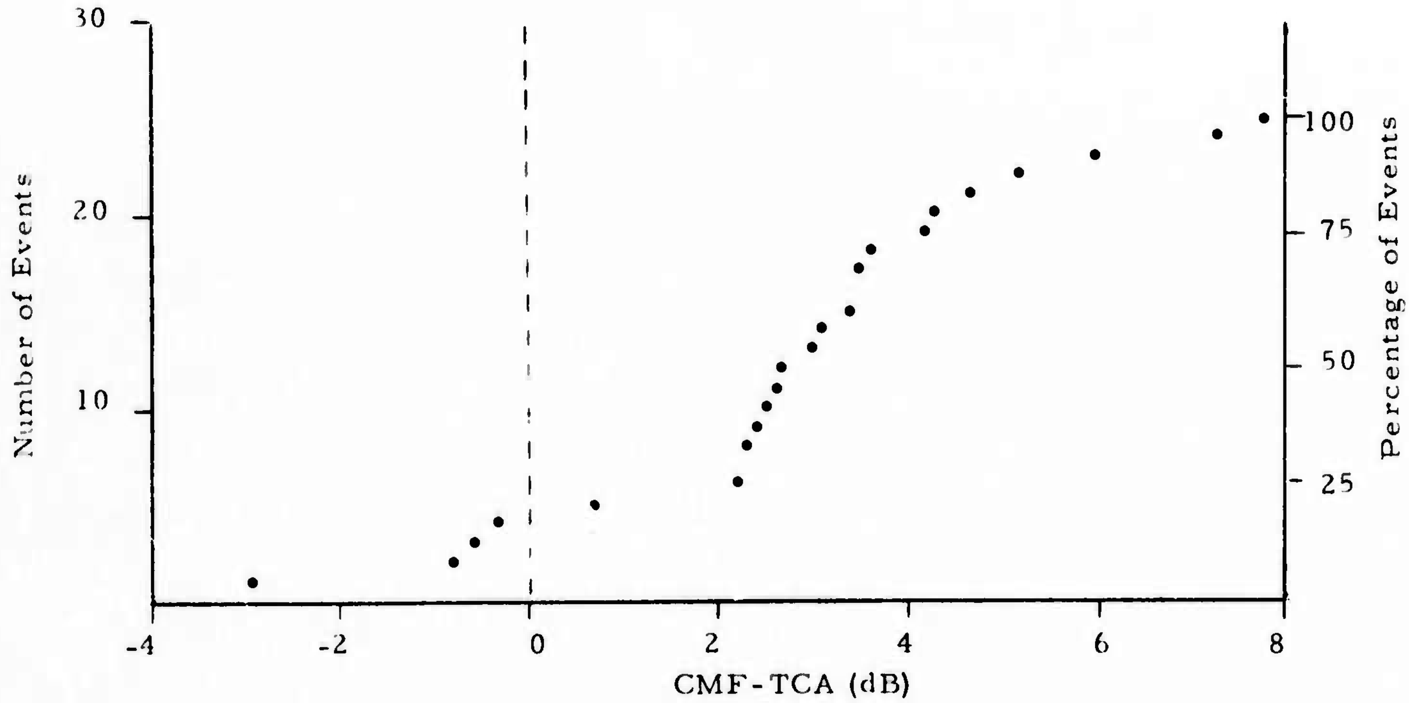



FIGURE VI-2

CUMULATIVE DISTRIBUTION OF CMF-RWMF SNNR IMP (A) AND CMF-TCA SNNR IMP (B) FOR GTUR TEST EVENTS (VERTICAL COMPONENT)

of the central Asia test events showed higher chirp SNNR improvements than three-component adaptive processor SNNR improvements. Figure VI-2 indicates that Greece-Turkey test events yielded about the same SNNR improvements on chirp and reference waveform matched filters, while approximately 85 percent of the test events from this region showed higher chirp SNNR improvements than three-component adaptive processor SNNR improvements. Therefore, by this criterion, chirp matched filters out-performed both the reference waveform and three-component adaptive processor on central Asia events. For Greece-Turkey events, chirp and reference waveform matched filters out-performed the three-component adaptive filter by the same amount. This is in agreement with the preceding judgment made on the basis of mean SNNR improvement and associated standard deviation.

### 2. Comparison of Detection Capabilities

The second point of comparison is the relative ability of the three techniques to detect signals which were not detected on the bandpass filter response. For the combined region, use of chirp matched filters resulted in a 130 percent increase in the number of events detected and use of reference waveform matched filters resulted in a 140 percent increase in the number of events detected. The use of the three-component adaptive processor resulted in only a 10 percent increase in the number of events detected. Thus, in terms of the increase in the number of events detected, use of chirp or reference waveform matched filters more than doubled the number of detections, while use of the three-component adaptive processor resulted in very little improvement in the number of detections.

An increase in the number of detections results in a decrease in the maximum-likelihood detection levels. This is illustrated by Table VI-2, which lists the 50 and 90 percent detection levels resulting from application

TABLE VI-2

DETECTION LEVELS DUE TO USE OF THE DATA ENHANCEMENT TECHNIQUES

| Technique | $m_b$ Detection Levels | |
|---|---|---|
| | 50% | 90% |
| Bandpass Filter | 4.72 $\pm$ 0.09 | 5.25 $\pm$ 0.17 |
| CMF | 4.04 $\pm$ 0.11 | 4.90 $\pm$ 0.20 |
| RWMF | 4.01 $\pm$ 0.11 | 4.91 $\pm$ 0.21 |
| TCA | 4.68 $\pm$ 0.10 | 5.31 $\pm$ 0.10 |

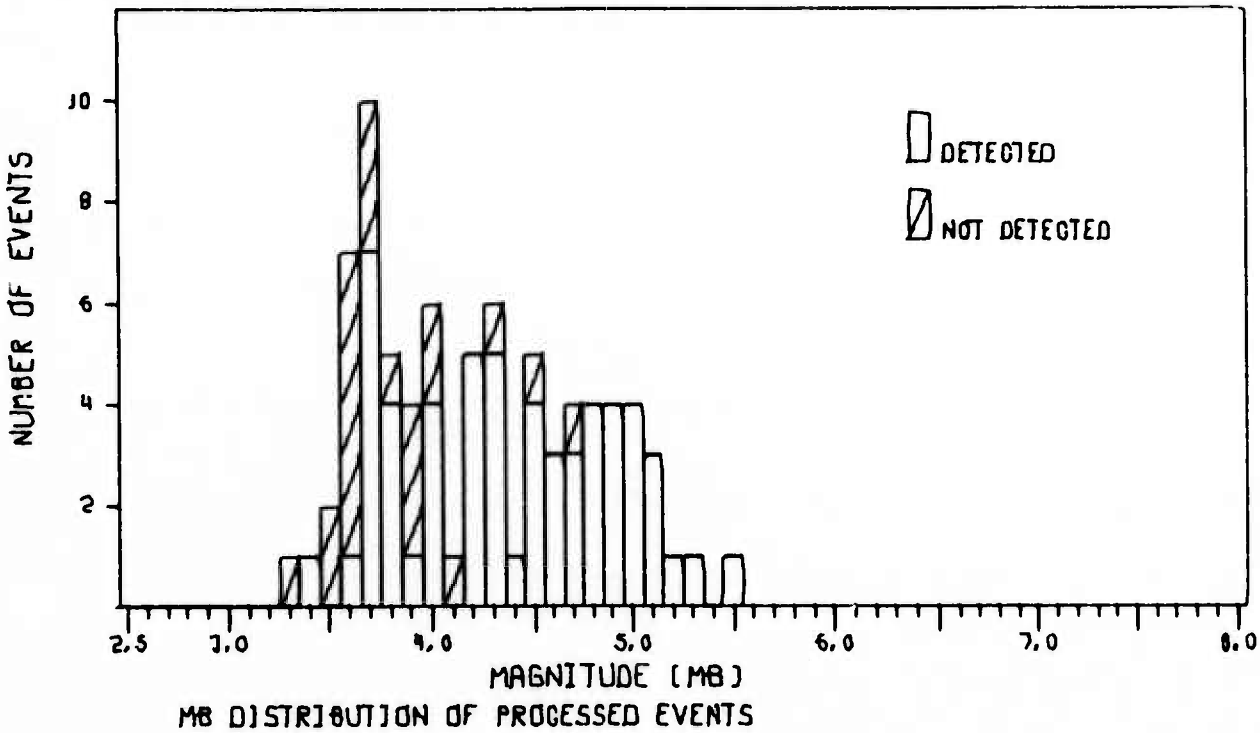
of the maximum-likelihood method to each of the three data enhancement techniques data sets. The bandpass filter detection levels are listed as a reference. All values are for the combined region. This table indicates that use of chirp or reference waveform matched filters decreases the 50 percent detection level by approximately 0.7 $m_b$ units and the 90 percent detection level by approximately 0.3 $m_b$ units. The changes in the 50 and 90 percent detection levels due to use of the three-component adaptive filter are too small to be significant.

It has been noted previously (Lane, 1973) that an SNNR improvement of 6 dB implies a reduction of about 0.3 in the bodywave magnitude at which 50 percent of all events are detected (the 50 percent detection level). This in turn implies a doubling of the total number of events detected. In this report, we have noted that use of chirp or reference waveform matched filters results in SNNR improvements of about 3 dB, a reduction of about 0.7 in the 50 percent detection level, and a factor of about 2.4 increase in the total number of events detected. The explanation for these apparent anomalies is as follows. First, the low mean SNNR improvements (less than 2 dB) computed at some stations probably do not represent the SNNR improvement produced when a station-event which was not detected on the bandpass response becomes visible on a matched filter response. This must be true for central Asia station-events of this type which are detected by reference waveform matched filters at Stations 2 and 11, since the mean SNNR improvements in these cases are negative. Thus, the SNNR improvements are probably higher than the approximate 3 dB improvement previously computed. Next, we recall that an event is considered to be detected only if it is detected at two or more stations. Those events which were detected on the bandpass filter response at only one station (a total of 19 events) were therefore listed as non-detected events. Therefore, a detection by a matched

filter at only one station other than the one at which it was detected on bandpass will change the detection status from non-detected to detected. Since it is more likely to detect an event using matched filters at one station than at two for a given SNNR improvement, we see that, for the VLPE network, it is possible to more than double the number of detections using matched filters when the mean SNNR improvement is less than 6 dB.

The factor of 2.4 increase in the total number of events detected due to use of chirp or reference waveform matched filters implies a reduction of 0.4 $m_b$ units in the 50 percent detection level. For this particular data base, however, we have a 0.7 $m_b$ unit reduction in the 50 percent detection level. To resolve this anomaly, we must have a larger data base, especially at the lower bodywave magnitude values.

Since the chirp and reference waveform matched filters yield approximately the same improvement in detection levels, let us consider what happens if the detection results are combined. In addition to the detection criteria used previously, an event is now considered to be detected if it is detected on either the chirp or reference waveform matched filter response. Twenty of the 79 events of the combined region were detected on the bandpass filter response. Use of this new detection criterion results in a total of 35 additional detections. The result of this is shown in Figure VI-3, which indicates that under this criterion, the 50 percent detection level is $3.74 \pm 0.12$ and the 90 percent detection level is $4.51 \pm 0.17$ for the combined region. Thus, the detection levels are lowered significantly (about 0.3 to 0.4 $m_b$ units) relative to those where detection is by chirp or reference waveform matched filter alone.



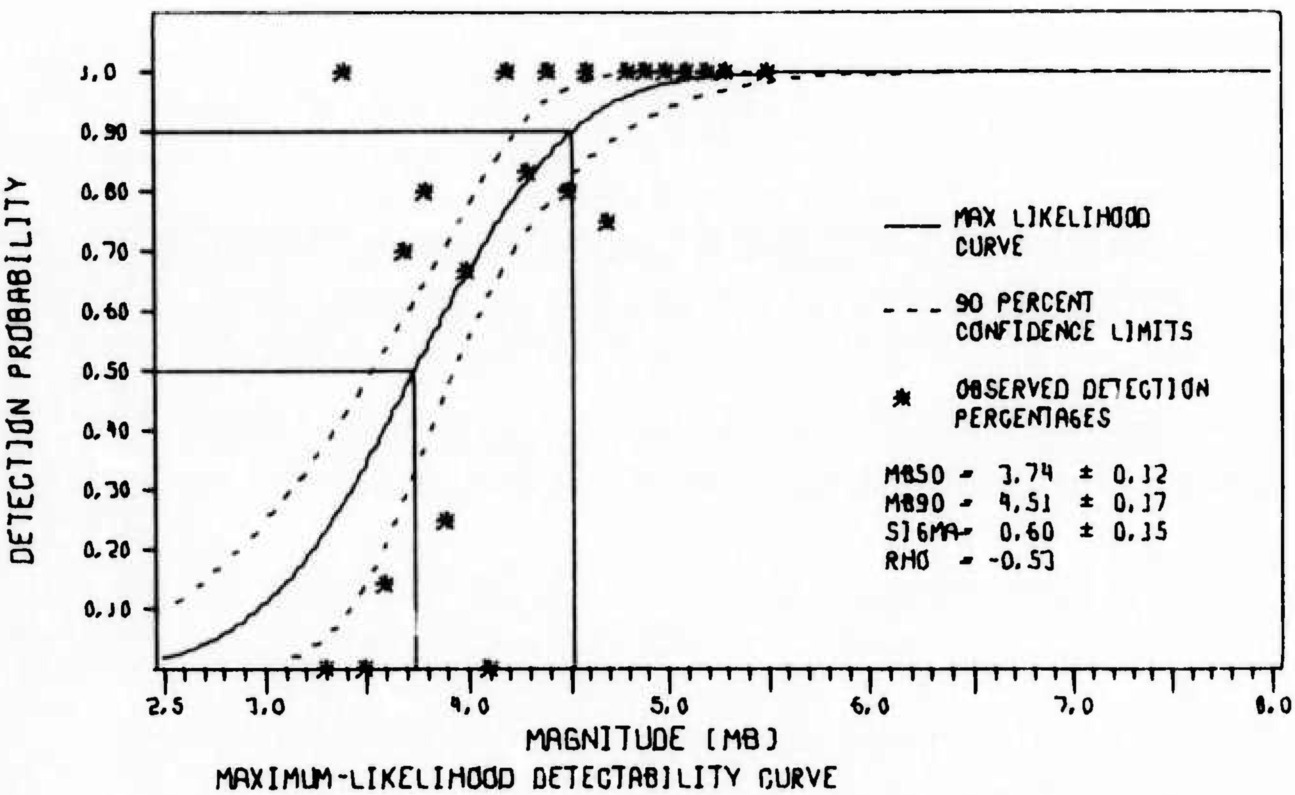




FIGURE VI-3

DETECTION STATISTICS FOR THE COMBINED REGION REQUIRING DETECTION ON CMF OR RWMF

### 3. Comparison of Surface-Wave Magnitudes

The point of comparison for surface-wave magnitudes derived from each of the techniques is the linear fit made to each set of $M_s : m_b$ data, where the $M_s$ values are for events not detected on the bandpass filter. For the combined region, the equations for these linear fits are:

$$M_s = 0.25\, m_b + 1.94 \quad \text{for CMF data}$$

$$M_s = 0.28\, m_b + 1.81 \quad \text{for RWMF data}$$

(No linear fit was computed for the TCA data, since only 12 data points were available.) From these equations, we see that the two matched filter methods produce values for surface-wave magnitudes which have essentially the same $M_s : m_b$ relationship. The small differences between the two relationships are mostly due to inaccuracies in the dB SNNR improvements.

To compare $M_s$ values computed from TCA data with those computed from matched filter data, we consider Table VI-3, which is a condensed version of Table B-1 of Appendix B. Table VI-3 lists only those events for which an $M_s$ value was computed from the CENA three-component adaptive processor data. This table shows that all but one of the TCA surface-wave magnitudes are higher than either of the corresponding matched filter surface-wave magnitudes. Since it is believed that the matched filter $M_s$ values are representative of the events detected, it will be necessary in future work to re-examine the manner in which $M_s$ is computed from TCA data.

## B. SUMMARY OF RESULTS

The major conclusions of this evaluation of the chirp matched filter, reference waveform matched filter, and three-component adaptive processor data enhancement techniques are:

TABLE VI-3

COMPARISON OF SURFACE-WAVE MAGNITUDES

| Event Number | $m_b$ | Surface-Wave Magnitude | | |
|---|---|---|---|---|
| | | CMF | RWMF | TCA |
| 885 | 4.8 | 3.13 | 2.69 | 3.03 |
| 887 | 4.7 | 2.72 | 2.60 | 3.07 |
| 914 | 4.6 | 3.03 | 3.39 | 4.17 |
| 955 | 4.2 | 3.37 | 3.38 | 4.47 |
| 961 | 4.3 | 3.08 | 3.04 | 3.52 |
| 1053 | 5.0 | 3.10 | - | 3.69 |
| 1084 | 4.5 | - | 3.03 | 4.22 |

- In the two seismic regions, the chirp matched filter technique outperformed the other two techniques in terms of overall mean LR SNNR improvement. (Since the standard deviations of the mean improvements were large, it is not meaningful to attempt a quantitative statement of relative performance.)

- Even though the overall mean LR SNNR improvement for a given technique applied to events from a given region may be low, the improvement in detection may be good.

- In terms of the increase in the number of events detected, the two matched filter techniques performed equally well and far outperformed the three-component adaptive processor technique.

- In terms of the detection level improvement of the network considered in this report, the two matched filter techniques performed equally well and far outperformed the three-component adaptive processor technique. When applied to the data set of this report, both yielded a 0.7 $m_b$ unit reduction in the 50 percent two-station detection level and a 0.3 $m_b$ unit reduction in the 90 percent detection level.

- When dealing with $M_s$ values of events detected only by a matched filter, $M_s$ values comparable to those from bandpass filtered data can be expected for $m_b$ values below the 50 percent bandpass filter detection level. For higher $m_b$ values, the $M_s$ values for events detected only by a matched filter can be expected to be much lower than the $M_s$ values determined from bandpass filtered data with comparable $m_b$ values.

- Overall, there is no clear superiority of one matched filter technique over the other for the set of stations considered in this report. Both are superior to the three-component adaptive processor technique as it is presently used.

- The poor performance of the three-component adaptive processor is due not to some intrinsic flaw in the method but to the unmatched instrumental phase responses between the horizontal and vertical components of the VLPE stations.

## C. FUTURE WORK

The following points should be considered in any future work along the lines of this report:

- The data base should be increased -- more events and stations should be investigated to better assess the capabilities of these techniques for presently defined regions. Furthermore, analysis of another region should be implemented to assess the capabilities of these techniques over a larger geographical event distribution.

- When sufficient data are available, the eastern Kazakh test region should be studied in terms of these data enhancement techniques.

- SNNR improvements for LQ should be determined.

- Individual stations need to be investigated in detail in terms of dB SNNR improvement and detection capability improvement due to use of these techniques.

- Mean delay times and associated standard deviations for matched filter responses should be determined. These are needed to improve the detection criteria.
- Before the TCA processor is used again, the phase and true amplitude responses of the stations must be determined and corrected for. The question of optimum overlap and gap length should also be resolved.
- More reliance could be put on the detection levels if the number of test events in the range $3.5 \leq m_b \leq 4.5$ were greater. Therefore, it is suggested that data from a local network or array be used to increase the number of test events.
- The PDP-15 interactive computing system should be implemented to expedite the matched filter data processing.

## SECTION VII

## ACKNOWLEDGEMENTS

We wish to thank T. W. Harley and D. G. Lambert for their many helpful discussions and critical reading of this paper. We especially wish to acknowledge S. Prahl for his work in adapting the three-component adaptive processor program to handle VLPE data.

## SECTION VIII

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## APPENDIX A

## DETECTION STATUS

In the following tables, a four-digit code gives the detection status of each station-event of the data base. (A one-digit zero code indicates that station-event was not included in the data-base.) The first digit indicates the detection status for the bandpass filter, the second digit indicates the detection status for the chirp matched filter, the third digit indicates the detection status for the reference waveform matched filter, and the fourth digit indicates the detection status for the three-component adaptive processor. A 1 indicates a detection, a 2 indicates a non-detection, and a 0 indicates that particular data enhancement technique was not applied.

TABLE A-1

CENTRAL ASIA DETECTION STATUS

| EVENT NUMBER | STATION NUMBER 2 | 5 | 6 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|
| 881 | 1111 | 1111 | 1111 | 1111 | 0 | 0 | 1111 |
| 884 | 1111 | 1111 | 1111 | 1111 | 1111 | 0 | 1111 |
| 885 | 2222 | 2111 | 2112 | 2122 | 2222 | 0 | 2112 |
| 886 | 2222 | 2222 | 2112 | 2212 | 2222 | 0 | 2222 |
| 887 | 2111 | 2211 | 0 | 0 | 0 | 0 | 2222 |
| 895 | 1111 | 2222 | 1111 | 0 | 0 | 0 | 0 |
| 896 | 2212 | 2222 | 0 | 2112 | 0 | 0 | 0 |
| 900 | 2222 | 2222 | 2222 | 0 | 0 | 0 | 0 |
| 902 | 2112 | 2210 | 2222 | 0 | 2222 | 0 | 2222 |
| 905 | 0 | 0 | 2122 | 0 | 2222 | 2222 | 2122 |
| 908 | 1111 | 0 | 1111 | 1111 | 1111 | 0 | 0 |
| 909 | 1111 | 0 | 2222 | 2222 | 0 | 0 | 0 |
| 910 | 2122 | 0 | 2222 | 2222 | 2222 | 0 | 0 |
| 911 | 1111 | 0 | 1111 | 1111 | 1111 | 0 | 0 |
| 913 | 0 | 0 | 2222 | 2112 | 2212 | 0 | 0 |
| 914 | 1111 | 0 | 2111 | 2112 | 2112 | 0 | 1111 |
| 915 | 1112 | 0 | 0 | 2121 | 2120 | 2222 | 2120 |
| 916 | 0 | 2122 | 1111 | 2222 | 1111 | 0 | 0 |
| 918 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 |
| 919 | 2222 | 0 | 0 | 2222 | 2222 | 2222 | 2122 |
| 920 | 2212 | 2220 | 0 | 2222 | 2122 | 2222 | 2222 |
| 922 | 2112 | 2120 | 0 | 2222 | 2222 | 2222 | 0 |
| 924 | 2212 | 2210 | 0 | 2122 | 2222 | 2222 | 2222 |
| 926 | 1112 | 0 | 1112 | 2122 | 0 | 2222 | 1111 |
| 929 | 1111 | 0 | 1111 | 1111 | 0 | 1111 | 1111 |
| 931 | 2222 | 2112 | 2212 | 2222 | 0 | 0 | 2112 |
| 938 | 2222 | 2212 | 2222 | 2122 | 0 | 0 | 2212 |
| 940 | 2222 | 2212 | 2112 | 2222 | 0 | 0 | 2122 |
| 946 | 1111 | 2210 | 2111 | 1112 | 0 | 0 | 1111 |
| 950 | 0 | 0 | 1111 | 1111 | 1111 | 0 | 0 |
| 952 | 0 | 0 | 1111 | 2222 | 2222 | 0 | 0 |
| 953 | 0 | 0 | 2112 | 0 | 0 | 0 | 0 |
| 954 | 0 | 0 | 1111 | 0 | 1111 | 0 | 0 |
| 955 | 0 | 0 | 1111 | 2121 | 2112 | 0 | 0 |
| 958 | 0 | 0 | 2122 | 2222 | 2222 | 0 | 0 |
| 961 | 0 | 0 | 2112 | 2111 | 2112 | 0 | 1111 |
| 965 | 0 | 0 | 1111 | 1111 | 1111 | 0 | 1111 |
| 978 | 0 | 1111 | 1111 | 0 | 1111 | 0 | 0 |
| 1017 | 0 | 0 | 2111 | 0 | 2122 | 0 | 2112 |
| 1033 | 0 | 2222 | 2111 | 2212 | 2212 | 0 | 2112 |
| 1034 | 0 | 2222 | 2112 | 2212 | 2222 | 0 | 2222 |
| 1044 | 0 | 0 | 2122 | 0 | 2212 | 0 | 1111 |
| 1047 | 0 | 2222 | 0 | 0 | 2222 | 0 | 0 |
| 1049 | 0 | 2122 | 2222 | 0 | 0 | 0 | 0 |
| 1051 | 0 | 0 | 2122 | 0 | 0 | 0 | 2222 |
| 1053 | 0 | 0 | 2122 | 0 | 2121 | 0 | 2122 |
| 1063 | 2110 | 0 | 2221 | 0 | 2222 | 0 | 2112 |
| 1064 | 2122 | 0 | 2212 | 0 | 0 | 0 | 2122 |
| 1067 | 0 | 0 | 2212 | 0 | 2222 | 0 | 2122 |
| 1069 | 0 | 0 | 2122 | 0 | 2222 | 0 | 1111 |
| 1084 | 2112 | 2222 | 2221 | 2222 | 2222 | 0 | 2112 |
| 1091 | 1112 | 0 | 2212 | 0 | 2212 | 0 | 2112 |
| 1092 | 1111 | 0 | 0 | 0 | 2212 | 0 | 2222 |

TABLE A-2

GREECE-TURKEY DETECTION STATUS

| EVENT NUMBER | STATION NUMBER 2 | 5 | 6 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|
| 890 | 1111 | 1111 | 1111 | 1111 | 1111 | 0 | 1111 |
| 891 | 2222 | 2221 | 2222 | 2222 | 2222 | 0 | 2222 |
| 892 | 2212 | 2222 | 0 | 2222 | 2222 | 0 | 2222 |
| 897 | 2111 | 2111 | 1111 | 1111 | 1111 | 1111 | 0 |
| 912 | 0 | 0 | 1111 | 0 | 2212 | 2212 | 0 |
| 927 | 2121 | 0 | 1111 | 2222 | 0 | 2122 | 2112 |
| 933 | 0 | 1110 | 1111 | 2212 | 0 | 0 | 0 |
| 934 | 2222 | 0 | 0 | 0 | 0 | 0 | 2222 |
| 939 | 2112 | 2212 | 0 | 0 | 0 | 0 | 2122 |
| 941 | 2222 | 2110 | 1111 | 0 | 0 | 0 | 0 |
| 944 | 2222 | 2220 | 2122 | 2222 | 0 | 0 | 2222 |
| 945 | 2222 | 2222 | 2222 | 2222 | 0 | 0 | 2222 |
| 947 | 2222 | 2220 | 2112 | 2222 | 0 | 0 | 2222 |
| 956 | 0 | 0 | 1111 | 1111 | 1111 | 0 | 0 |
| 957 | 0 | 0 | 1111 | 0 | 0 | 0 | 2222 |
| 968 | 0 | 0 | 1111 | 0 | 0 | 0 | 0 |
| 971 | 0 | 1111 | 0 | 2222 | 0 | 0 | 0 |
| 972 | 0 | 0 | 1111 | 2222 | 0 | 0 | 0 |
| 983 | 0 | 1111 | 1111 | 0 | 1111 | 0 | 0 |
| 1021 | 0 | 2222 | 0 | 0 | 2222 | 0 | 0 |
| 1028 | 0 | 2222 | 1111 | 2122 | 0 | 0 | 0 |
| 1042 | 0 | 2212 | 1111 | 0 | 0 | 0 | 2222 |
| 1048 | 0 | 2212 | 0 | 0 | 2222 | 0 | 2122 |
| 1052 | 0 | 2222 | 1111 | 0 | 2222 | 0 | 2222 |
| 1073 | 2122 | 2222 | 2112 | 0 | 2222 | 0 | 0 |
| 1081 | 2122 | 1111 | 0 | 0 | 2112 | 0 | 2222 |
| 1086 | 2222 | 0 | 0 | 0 | 2122 | 0 | 2112 |
| 1087 | 2212 | 2222 | 2112 | 0 | 2222 | 0 | 2122 |

# APPENDIX B

# SURFACE-WAVE MAGNITUDES

The following tables list surface-wave magnitudes computed from chirp matched filter, reference waveform matched filter, and three component adaptive processor data. These magnitude values are network averages with one or more stations reporting. A value of zero indicates that no magnitude was computed.

The tables contain values only for those station-events which were detected by the data enhancement techniques but not by the bandpass filter. All matched filter values were computed from LR-V data.

TABLE B-1

SURFACE-WAVE MAGNITUDES FOR CENTRAL ASIA EVENTS

| EVENT | BODY WAVE | SURFACE WAVE MAG. | | |
| --- | --- | --- | --- | --- |
| NUMBER | MAGNITUDE | CMF | RWMF | TCA |
| 885 | 4.9 | 3.13 | 2.69 | 3.03 |
| 886 | 3.8 | 2.90 | 3.16 | 0.0 |
| 887 | 4.7 | 2.72 | 2.60 | 3.07 |
| 896 | 4.8 | 0.0 | 2.87 | 0.0 |
| 902 | 3.7 | 2.53 | 2.63 | 0.0 |
| 905 | 3.8 | 3.16 | 0.0 | 0.0 |
| 913 | 3.7 | 3.13 | 2.96 | 0.0 |
| 914 | 4.6 | 3.03 | 3.39 | 4.17 |
| 915 | 4.8 | 4.65 | 0.0 | 5.61 |
| 920 | 3.7 | 2.93 | 2.46 | 0.0 |
| 922 | 4.0 | 2.62 | 2.82 | 0.0 |
| 924 | 4.3 | 3.19 | 0.0 | 0.0 |
| 926 | 4.9 | 3.23 | 0.0 | 0.0 |
| 931 | 3.7 | 0.0 | 3.25 | 0.0 |
| 938 | 4.0 | 3.29 | 0.0 | 0.0 |
| 940 | 5.0 | 3.09 | 0.0 | 0.0 |
| 955 | 4.2 | 3.37 | 3.38 | 4.47 |
| 958 | 3.9 | 2.91 | 0.0 | 0.0 |
| 961 | 4.3 | 3.08 | 3.04 | 3.52 |
| 1017 | 4.2 | 3.03 | 3.06 | 0.0 |
| 1033 | 4.6 | 0.0 | 2.97 | 0.0 |
| 1034 | 3.7 | 3.05 | 3.06 | 0.0 |
| 1044 | 3.4 | 0.0 | 3.53 | 0.0 |
| 1049 | 3.6 | 2.66 | 0.0 | 0.0 |
| 1051 | 3.6 | 2.86 | 0.0 | 0.0 |
| 1053 | 5.0 | 3.10 | 0.0 | 3.69 |
| 1064 | 3.8 | 4.10 | 4.05 | 0.0 |
| 1067 | 3.5 | 2.97 | 2.83 | 0.0 |
| 1069 | 3.8 | 3.05 | 0.0 | 0.0 |
| 1084 | 4.5 | 0.0 | 3.03 | 4.22 |
| 1091 | 3.7 | 2.82 | 3.28 | 0.0 |

## TABLE B-2

## SURFACE-WAVE MAGNITUDES FOR GREECE-TURKEY EVENTS

| EVENT NUMBER | BODY WAVE MAGNITUDE | SURFACE WAVE MAG. CMF | RWMF | TCA |
|---|---|---|---|---|
| 897 | 5.0 | 3.37 | 2.14 | 3.13 |
| 912 | 4.5 | 0.0 | 3.23 | 0.0 |
| 927 | 4.6 | 3.88 | 0.0 | 3.05 |
| 933 | 4.7 | 0.0 | 3.29 | 0.0 |
| 939 | 4.3 | 2.96 | 2.41 | 0.0 |
| 941 | 4.3 | 2.32 | 0.0 | 0.0 |
| 944 | [illegible].9 | 2.63 | 0.0 | 0.0 |
| 947 | 3.3 | 2.56 | 2.68 | 0.0 |
| 1028 | 3.6 | 3.16 | 0.0 | 0.0 |
| 1042 | 3.7 | 0.0 | 2.39 | 0.0 |
| 1073 | 3.7 | 3.06 | 0.0 | 0.0 |
| 1081 | 4.4 | 3.10 | 3.53 | 0.0 |
| 1086 | 4.7 | 4.43 | 4.39 | 0.0 |
| 1087 | 4.0 | 2.55 | 0.0 | 0.0 |